See 1473

FG

12

AD

ADA023946

AVSCOM Report No. 76-12

Production Engineering Measures Program
Manufacturing Methods and Technology

# COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM AND STEEL STRUCTURAL PARTS (PHASE I)

VIJAY NAGPAL and TAYLAN ALTAN
BATTELLE, Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201



March 1976

AMMRC CTR 76-6

Final Report Contract Number DAAG46-75-C-0054

Approved for public release; distribution unlimited.

Prepared for
U.S. ARMY AVIATION SYSTEMS COMMAND
St. Louis, Missouri 63166

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

Mention of any trade names or manufacturers in this report shall not be construed as advertising nor as an official indorsement or approval of such products or companies by the United States Government.

**DISPOSITION INSTRUCTIONS**

Destroy this report when it is no longer needed.
Do not return it to the originator.

AD

AVSCOM Report No. 76-12

Production Engineering Measures Program
Manufacturing Methods and Technology

# COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM AND STEEL STRUCTURAL PARTS (PHASE 1)

VIJAY NAGPAL and TAYLAN ALTAN
BATTELLE, Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

March 1976

AMMRC CTR 76-6

Final Report          Contract Number DAAG46-75-C-0054

Approved for public release; distribution unlimited.

Prepared for
U.S. ARMY AVIATION SYSTEMS COMMAND
St. Louis, Missouri 63166

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

## FOREWORD

This final report on "Computer-Aided Design and Manufacturing for Extrusion of Aluminum, Titanium, and Steel Structural Parts - Phase I" covers the work performed under Contract DAAG46-75-C-0054, with Battelle's Columbus Laboratories, from February 10, 1975 to February 10, 1976.

The project was supported by the Army Materials and Mechanics Research Center, Watertown, Massachusetts, and by the U.S. Army Aviation Systems Command, St. Louis, Missouri. The (AVSCOM) liaison engineer was Mr. Roger Spangenberg. The technical supervision of this work was under Mr. Roger Gagne of AMMRC.

This project has been conducted as part of the U.S. Army Manufacturing Methods and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques, or equipment to ensure the efficient production of current and future defense programs.

This program has been conducted in the Metalworking Section of Battelle's Columbus Laboratories, with Mr. T. G. Byrer, Section Manager. The principal investigators of the program are Dr. Vijay Nagpal, Staff Scientist, and Dr. Taylan Altan, Research Leader. Other Battelle staff members have been consulted throughout the program as needed.

In conducting the model-extrusion trials, which represent an important portion of the Phase-I work, the principal investigators of the program cooperated with Air Force personnel. The trials were carried out using the 700-ton horizontal extrusion press of the Air Force Materials Laboratory at Wright-Patterson Air Force Base, Ohio. The authors gratefully acknowledge the assistance of Messrs. A. M. Adair, V. DePierre, F. Gurney, and M. Myers in conducting these trials.

## PROGRAM SUMMARY

The overall objective of this manufacturing-technology program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys. It is expected that the application of CAD/CAM in extrusion will expand the capabilities of the extrusion process and reduce the cost of extruding and finishing structural components used in manufacturing military aircraft.

The Phase-I work, reported here, was devoted to develop the CAD/CAM method for extruding a modular shape of rectangular cross section using lubricated, streamlined dies. The results, reported here, indicate that the objectives of Phase-I work has been fully achieved.

The success of any manufacturing-development program depends mainly upon two factors:

(1) The technical quality and the usefulness of the development work

(2) The acceptance, the application, and the use of the results developed in the program, by the industry and others active in that field.

Therefore, in addition to fulfilling the technical requirements of Phase-I work, initial contacts were made with companies extruding aluminum and titanium alloys, in order to emphasize the practical and industrial aspects of these program results.

### Introduction of CAD/CAM in Extrusion

Large numbers of extruded aluminum, titanium, and steel components are used in the manufacture and assembly of military hardware. Most of these components are extruded by conventional hot extrusion techniques. Although the extrusion process has been a viable manufacturing process for more than a generation, with the exception of glass lubrication in high-temperature extrusion, hardly any improvements have been made. Extrusion technology is still based largely upon empirical cut-and-try methods which result in the high cost of extruded products. Most of the tool design and manufacturing work for extrusion is still done by the intuitive and empirical methods. Therefore, extrusion die design and manufacturing is still considered an art rather than a science. In this respect, the state of the art in the extrusion technology

is very similar to that of other metal-forming processes. The scientific and engineering methods, successfully used in other engineering disciplines, have not been utilized in extrusion. This situation can be explained by the inherent complexity of the extrusion process. The difficult-to-predict metal flow, the simultaneous heat generation and transfer which takes place during the process, the friction at the material-tool interfaces, and the metallurgical variations, make the extrusion process difficult to analyze from the engineering point of view. However, recently, computer-aided techniques for analyzing and simulating metal-flow and deformation mechanics have been developed and proven. The application of these techniques along with advanced numerical machining (NC) technology allows the practical use of CAD/CAM in extrusion technology.

The Phase-I work illustrated the feasibility of applying CAD/CAM in extrusion-die design and manufacture, and in process planning.

## Program Approach

The Phase-I work was completed by performing the following major tasks:

(1) Review the present state of the art in extrusion-die design and characterize the most commonly used extruded shapes.

(2) Divide these shapes into geometric modules and develop the CAD/CAM techniques for extruding a modular shape.

(3) Expand the results of the analysis, developed for a modular shape, to more practical simple shapes, such as L's, T's, and rectangles.

(4) Perform extrusion trials with a rectangular shape to demonstrate the validity of CAD/CAM techniques.

## Outline of the Final Report (Phase I)

Following the major steps conducted in the Phase-I effort, this final report is organized in three chapters as follows:

Chapter 1: Die Design for Extrusion of Structural Shapes

Chapter 2: CAD/CAM of a Streamlined Die for a Modular Shape

Chapter 3: CAD/CAM of Streamlined Dies for Lubricated Extrusion of Simple Structural Shapes.

Each chapter can be read separately, without having to go through the entire report, to find information related to any of the major tasks conducted in this program. Thus, the use and readability of this final report is enhanced.

Chapter 1 summarizes the state of the art on die design for extruding structural shapes. This chapter also reviews (a) the conventional nonlubricated extrusion of aluminum alloys, (b) the recent development efforts on lubricated extrusion of aluminum alloys, and (c) the technology and die design for extruding steels, titanium alloys, and high-temperature alloys.

Chapter 2 describes the work conducted toward applying CAD/CAM techniques to the extrusion of a modular shape, which was selected to be an ellipse, approximating a rectangle. This chapter also includes the analysis and simulation of the extrusion process as well as a description of the NC machining techniques suggested for manufacturing the extrusion dies.

Chapter 3 describes the application of CAD/CAM techniques to extrude simple structural shapes, such as L's, T's, rectangles, and triangles. Numerical techniques are given for lubricated extrusion (a) to define the surface of "streamlined" dies", and (b) to manufacture these dies by a combination of Numerical Control (NC) machining and Electro-Discharge Machining (EDM). Chapter 3 also describes the extrusion trials conducted with a rectangular shape, and discusses the comparison of predictions made by CAD/CAM techniques with the measurements made during the extrusion trials. The results indicate that the CAD/CAM techniques, developed in this Phase-I work, are capable of predicting extrusion pressures and metal flow in "streamlined extrusion" with acceptable accuracy.

Chapter 3 summarizes the Phase-I work, including the most significant aspects of the technical effort conducted in this program.

# CHAPTER I

## "DIE DESIGN FOR EXTRUSION OF STRUCTURAL SHAPES"

## TABLE OF CONTENTS



## LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

## CHAPTER I

## "DIE DESIGN FOR EXTRUSION OF STRUCTURAL SHAPES"


### ABSTRACT

This chapter summarizes the state of the art on die design for extruding structural shapes. The conventional dry extrusion of aluminum shapes is discussed and the limited amount of information, available on lubricated extrusion of aluminum alloys, is summarized. The extrusion technology and die design for steels, titanium, and high-temperature alloys are critically reviewed. Past work on extrusion technology indicates that, with improved die design, lubricated extrusion of hard-aluminum alloy shapes could become practical and the extrusion of high-temperature alloys can be significantly improved.


### INTRODUCTION

In recent years, a considerable amount of work has been conducted on the improvement of the extrusion process for producing shapes from aluminum, steel, titanium, and high-temperature alloys. This work has resulted in the development of some new extrusion techniques, such as extrusion of steel and high-strength alloys with glass lubrication. However, the overall extrusion technology still remains to be largely based on empirical cut-and-dry methods. Most of the extrusion die design and manufacturing work is still considered an art rather than a science. This situation can be explained by the inherent complexity of the extrusion process. The difficult to predict metal flow, the simultaneous heat generation and transfer which takes place during the process, the friction at the material-tool

interfaces, and the metallurgical variations make the extrusion process very difficult to analyze from an engineering point of view. Consequently, there remains still considerable development work to be done in order to upgrade the extrusion technology to the level of an advanced manufacturing process, for producing sound parts at moderate costs.

Current practices followed for extruding aluminum alloys are quite different from those used for extruding steel, titanium, and high-temperature materials. Therefore, the extrusion of aluminum is discussed separately and the limited amount of information available on lubricated extrusion of aluminum is reviewed. This subject is of special interest to this project since the project has the primary objective to develop computer-aided die design and manufacturing techniques for lubricated and streamlined extrusion of aluminum alloys, titanium alloys, and steels. After reviewing the extrusion technology for steels and titanium alloys, the chapter presents some suggestions regarding the approach to die design. These suggestions are evaluated in detail later in the program.

In preparing the present review, it is assumed that the reader is familiar with the general aspects of the extrusion processes.[1,2] The information, summarized in this chapter, relates particularly to process variables and to die design in extrusion.

## EXTRUSION OF SHAPES FROM ALUMINUM ALLOYS

A variety of aluminum alloys (1000 to 7000 series) are extruded and find large numbers of commercial and military applications. Among all these alloys, the high-strength aluminum alloys (2000 and 7000 series) are most widely used for aircraft applications. Other alloys, such as 1100, 3003, 6061, 6062, 6063, and X6463, are used for manufacturing goods for a variety of applications, such as construction, household appliances, and transportation.[3]

## The Extrusion Process

The two most significant extrusion processes for aluminum are the direct and indirect extrusion, and these are schematically illustrated in Figure 1-1. With aluminum, lubricant is not normally used.[(1)] The extrusion method, which uses no lubrication between the billet, the container, and the die, is used to produce complex shapes with excellent surface finish and close-dimensional tolerances. These shapes are considered net extrusions and they are used in as-extruded form, after necessary straightening and surface-coating operations.[(1)]

In nonlubricated extrusion of aluminum, the billet is extruded through a flat-faced, or shear-faced die. As the pressure is applied to the end of the billet, internal shearing occurs across the planes within the billet, and fresh metal is forced out through the die orifice. This fresh metal accounts for the bright finish obtained on extruded aluminum shapes. With this technique, however, very high extrusion forces are required because of internal shearing between the flowing and the stationary metal along the container surface and at the die corners, Figure 1-1. The energy dissipated by internal shearing, or redundant work, represents energy that is converted into heat, and results in a gradual increase of the product temperature as the extrusion proceeds. If not controlled, this adiabatic heating can be sufficient to cause hot shortness and melting in the extruded material.[(1)]

## Extrusion Speed and Temperatures

In order to increase the production rate in extrusion, it is desirable to achieve as high an extrusion ratio as possible. Therefore, with hard aluminum alloys, the maximum possible billet preheat temperatures are utilized. This combination of high-extrusion ratio, high-starting billet temperature, and the danger of overheating due to redundant work, necessitates very low extrusion speeds for extruding a sound product. Thus, a ram speed of 1/2 inch/minute is quite common. With a typical extrusion ratio of 40:1, exit speeds of the extrusion can be in the order of 2 to 4

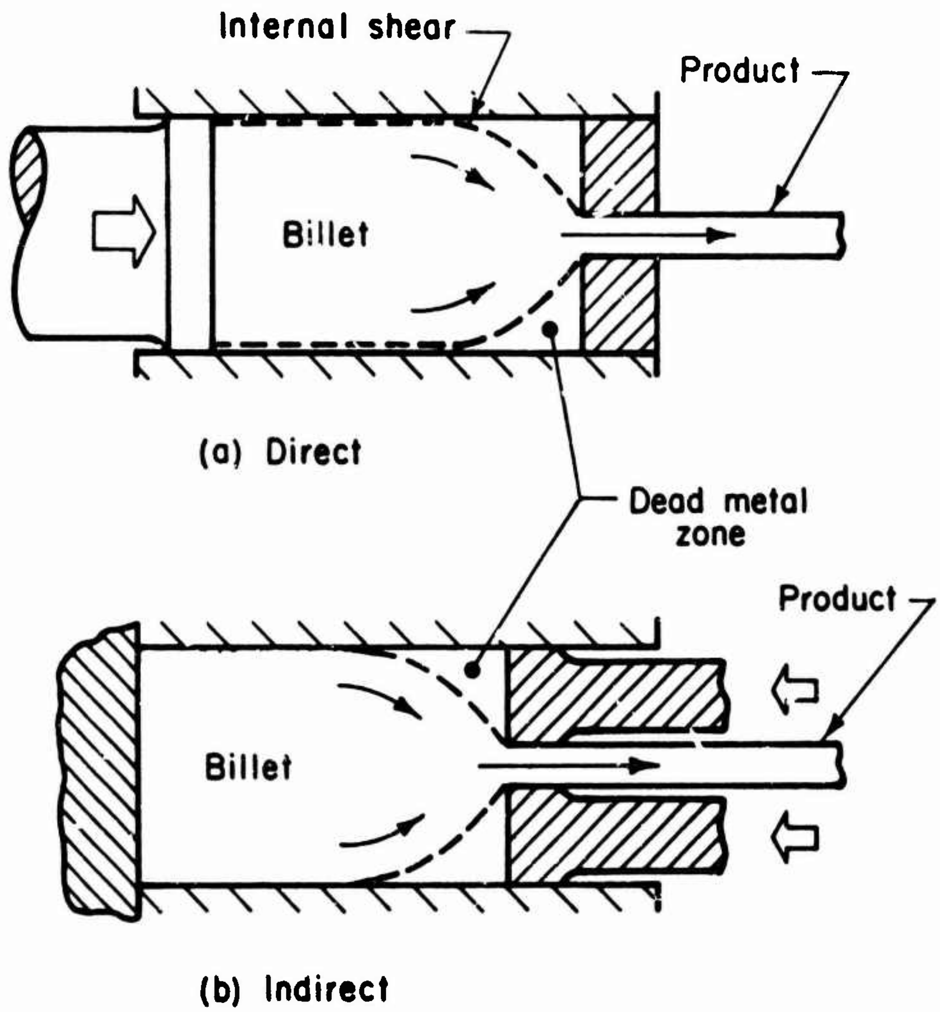



FIGURE 1-1. SCHEMATIC OF DIRECT AND INDIRECT EXTRUSION OF ALUMINUM ALLOYS WITHOUT A LUBRICANT

feet/minute. Figure 1-2 shows the range of extrusion speeds, at exit, used for different aluminum alloys.[4] It is of interest to note that for soft alloys the speeds are reasonably high; however, for hard alloys, such as 2024 and 7075, extrusion rates are quite low. Consequently, the use of lubrication in extruding high-strength alloys can be expected to increase the extrusion rate and to reduce extrusion costs. However, lubrication cannot offer any significant advantages in extruding the soft alloys.

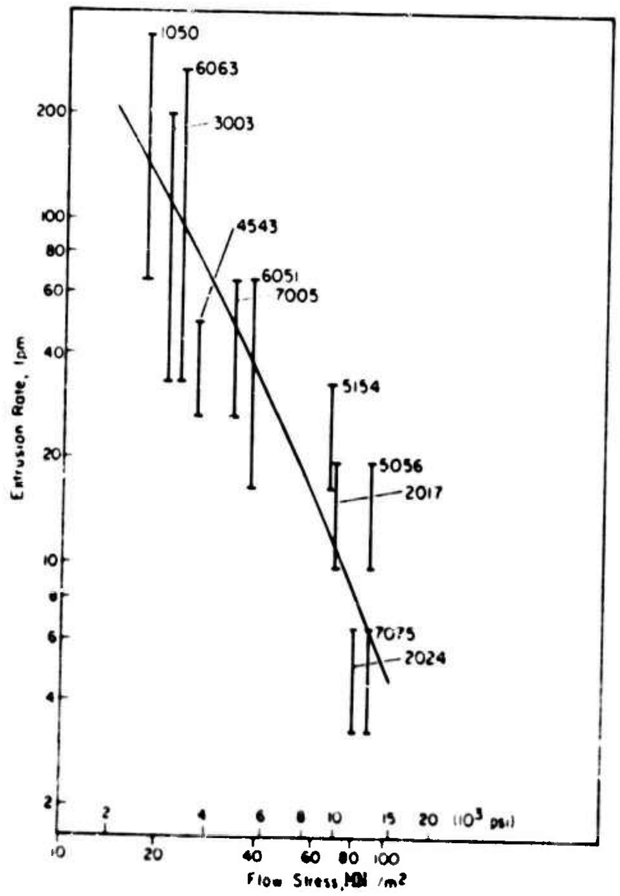



**FIGURE 1-2. RELATION BETWEEN EXTRUSION RATE AND FLOW STRESS FOR VARIOUS ALUMINUM ALLOYS[4]**

By far, the greater proportion of all aluminum extrusions consists of heat-treated alloys and all of these have a critical temperature associated with the presence of low-melting intermetallic compounds that restricts the permissible extrusion temperatures and speeds.[5] Because of the slow speed of extrusion, the tooling temperature is maintained close to, about 50 C to 100 C below, that of the billet, so that chilling of the billet is minimized.[5] Akeret[6] conducted theoretical and practical studies of temperature distribution in the extrusion of aluminum alloys under conditions in which the container and tools were initially below, equal to, or above the initial billet temperature. He deduced that, for the particular experimental conditions employed, the rise of temperature under adiabatic conditions would be about 95 C. For practical purposes, it can be estimated that, in extruding high-strength alloys, the maximum temperature rise likely to be encountered will not exceed 100 C. For the soft alloys where lower specific pressures are required, the temperature rise under normal production conditions is not likely to exceed 50 C.[5]

At Battelle's Columbus Laboratories, computer programs have been developed for predicting temperatures in extrusion of rods and tubes from various materials.[7,8] As seen in Figure 1-3, based on theoretical predictions as well as on experimental evidence, the product temperature increases as extrusion proceeds. The temperature at the product surface is higher than the temperature at product center. This is illustrated in Figure 1-4 for given extrusion conditions. Thus, it is seen that the surface temperature of the product may approach the critical temperature where hot shortness may occur, only towards the end of the extrusion cycle. The temperature of the extruded product, emerging from the die, is one of the essential factors influencing the product quality. Therefore, an ideal procedure for establishing the maximum speed of extrusion at all times would be to measure this temperature and to use it for controlling the ram speed. This procedure was proposed in an early patent,[9] but the problem of obtaining an accurate and continuous temperature measurement of the extruded product remains unsolved. Methods for measuring the product temperature by using various types of contact thermocouples, or by radiation pyrometry, did not prove to be practical.

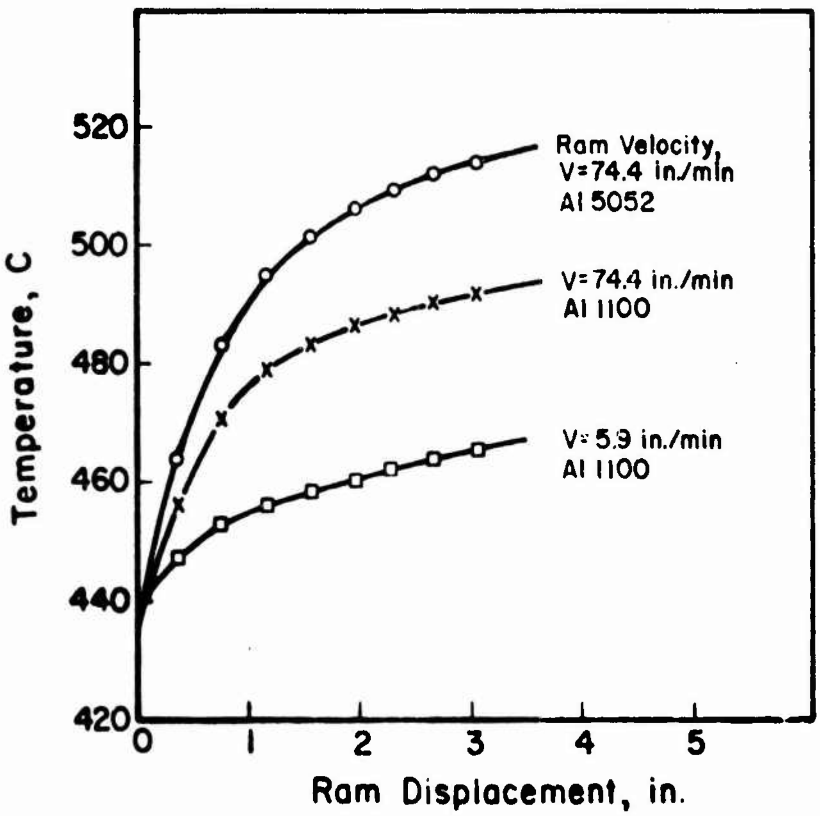
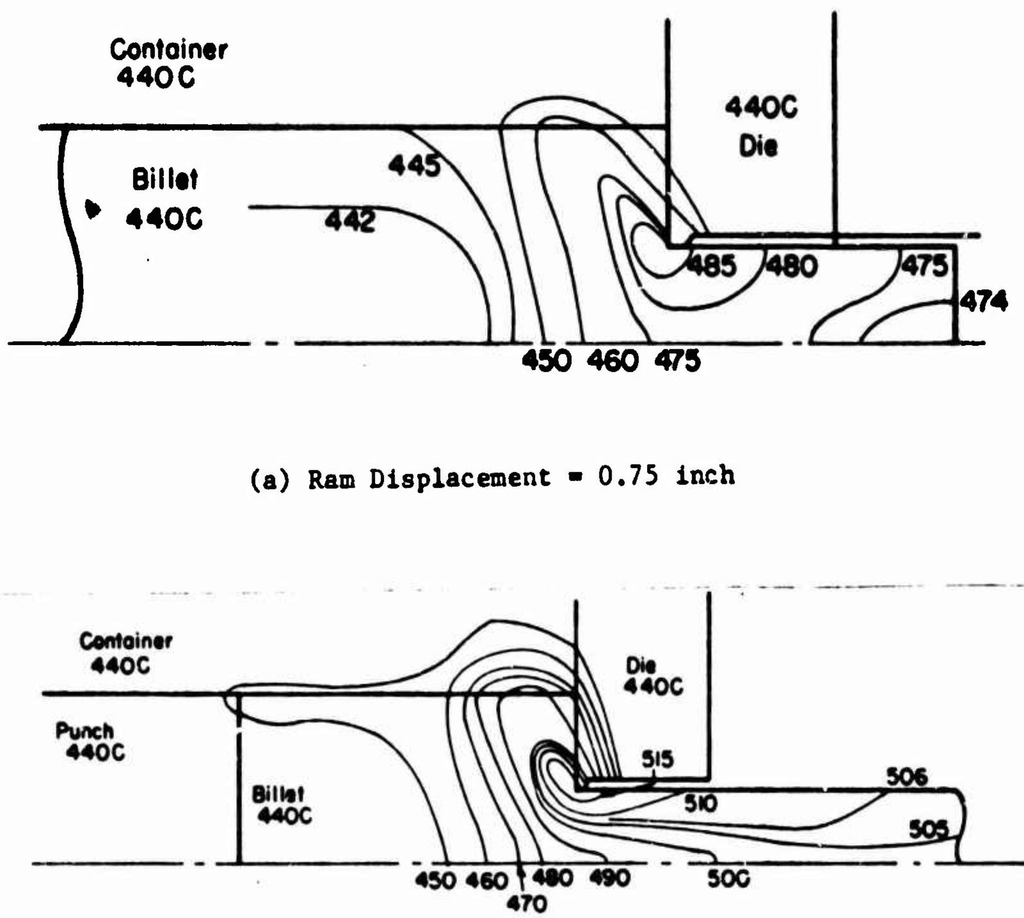



FIGURE 1-3. SURFACE TEMPERATURES OF THE EXTRUDED PRODUCT AT THE EXIT FROM THE DIE (Reduction = 5:1, Billet Diameter = 2.8 in., Billet Length = 5.6 in., Initial Billet and Tooling Temperature = 440 C)(7)




(a) Ram Displacement = 0.75 inch



(b) Ram Displacement = 3.7 inch

FIGURE 1-4. TEMPERATURE DISTRIBUTIONS IN EXTRUSION OF AL 5052 ALLOY ROD THROUGH A FLAT DIE (Reduction = 5:1, Ram Speed = 74.4 in/min, Billet Diameter = 2.8 in, Billet Length = 5.6 in, Initial Billet and Tooling Temperatures = 440 C)[7]

Laue[10] was the first to propose a system for isothermal extrusion in which the ram speed variation, necessary to keep the product temperature within the required limits, was pre-established. In presses, designed to operate on this principle, the working stroke is divided into zones, each having a preset speed. In a press used for extruding the high-strength alloys, a saving of 60 percent in time was claimed. This saving would certainly be less in the case of more easily extruded alloys. According to Fernback,[11] to make full use of the isothermal-extrusion principle, it would be necessary to predetermine, by trial and error, a large number of speed programs for extruding different alloys and products.

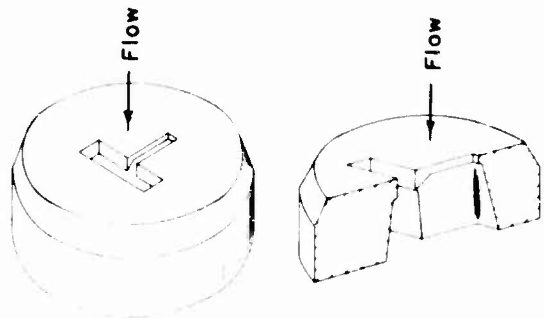
In extrusion of aluminum alloys, temperature variations in the emerging product can be reduced by imposing a temperature gradient in the billet.[5] The hot end of the billet is entered into the container such that it is extruded first, while the temperature of the cooler end increases during the extrusion. This practice is not entirely satisfactory because of the relatively high-thermal conductivity of aluminum alloys, so that if any delays occur in a programmed sequence, the temperatures in the billet tend to become uniform throughout the billet length. A better method is to water quench the back end of the billet while transferring it from the furnace and the press-feed table to the container. Neither method is found to be accurate and reproducible.[5] Another approach that has been used to increase the extrusion speed is to use water-cooled dies.[12]

For controlling and predicting the variation of the ram speed during extrusion, it may be useful to use computer simulations to predict the temperature rise during the process.[7,8] The purpose of this computer-aided speed control would be to have maximum extrusion speeds with minimum variation in temperature in the extruded product.

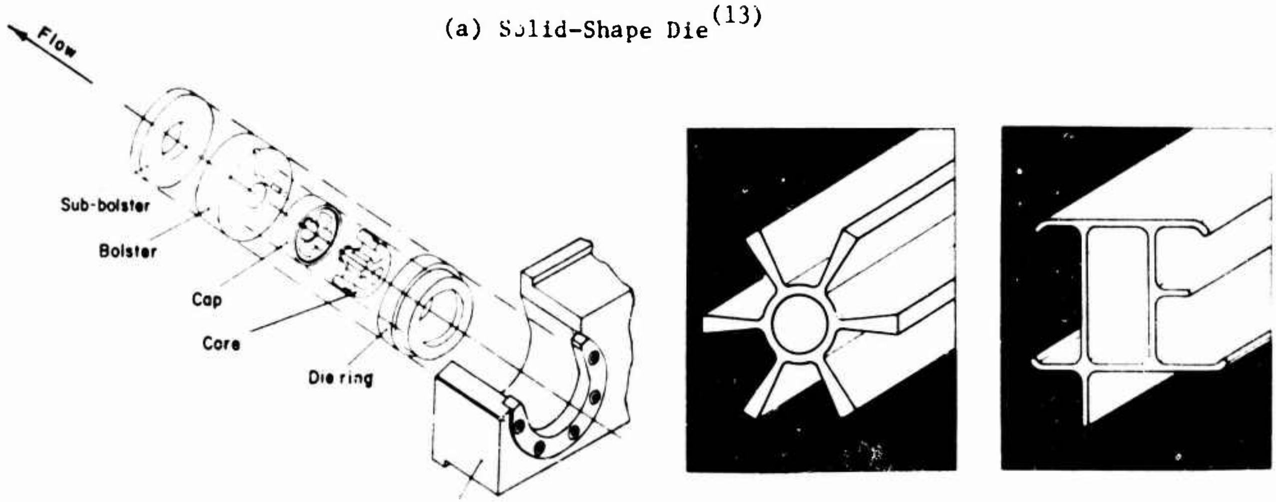
## Dies for Conventional Aluminum Extrusion

There are four general designs of flat-faced dies for extruding aluminum, as shown in Figure 1-5.[13-15]

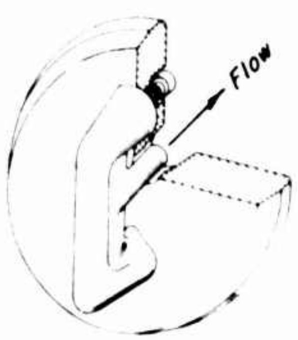
(1) Solid shape
(2) Porthole
(3) Bridge
(4) Baffle or feeder plate.



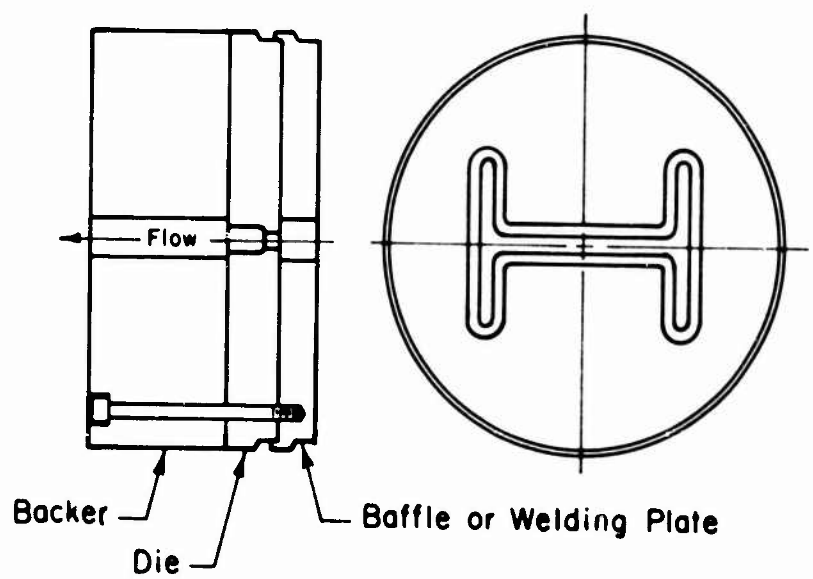

(a) Solid-Shape Die[13]




(b) Porthole Die With Tooling Assembly and Example Shapes Extruded Through Such a Die[15]




(c) Bridge Die[13]




(d) Baffle, or Feeder Plate Die[14]

FIGURE 1-5. VARIOUS TYPES OF EXTRUSION DIES FOR ALUMINUM ALLOYS[13-15]

The solid-shape dies are primarily used for extruding solid shapes. These dies are made by machining an opening of the desired shape in the die block as shown in Figure 1-5a. The porthole die design, shown in Figure 1-5b, has porthole openings in the top face of the die from which material is extruded into two or more segments, and then, beneath the surface of the die, welded and forced through the final shape configuration to form a part. The tubular portion of the extruded shape is formed by a mandrel attached to the lower side of the top die segment. This provides a fixed support for the mandrel and a continuous hole in the extruded part. Figure 1-5b shows typical complex parts that can be made through the use of a porthole type arrangement.

Bridge dies are quite similar to the porthole dies and are also used for extruding hollow products. The "bridge" which divides the metal extends into the container, Figure 1-5c. Compared to porthole dies, the bridge dies are less rigid. However, the removal of the extrusion, left in the container at the completion of the extrusion cycle, is more difficult with porthole dies than with bridge dies.

Another interesting type of die design, shown in Figure 1-5d, is the so-called baffle or feeder-plate die, which is used to serve several purposes. The feeder plate provides a uniform feed of metal into the cavity of the die, which induces flow control and assists in maintaining the contour of the extruded section. It also permits the next billet to partially weld itself to the material in the cavity, ensuring a straight run out for the next extrusion. This method helps to extrude straighter extrusions and to reduce scrap. These feeder plates are used for single and multi-hole dies of all sizes and shapes. Other die designs used for specific products are illustrated in References 14 and 15.

In conventional unlubricated extrusion with flat-faced dies, the material always shears against itself and forms a dead, or stationary zone, at the die face, Figure 1-1. The formation of the dead zone minimizes the overall rate of energy dissipation, but in general, does not give, in extrusion of shapes, uniform metal flow at the die exit. Nonuniform metal flow can result in twisting and bending of the emerging product. To prevent this, the flow rate is controlled through proper design of die land and by proper positioning of die cavity with respect to the billet center.[16]

Die-Land Design and Correction

There is a general agreement that longer die lands improve the tolerances and straightness of the extruded products. However, the extrusion load increases with increasing length of the die land. Thus, the die land must be designed to give uniformly strained product within desired tolerances and without excessive extrusion pressure.

In lubricated cold-rod extrusion, Keegan[17] gives some approximate rules for estimating the land length in dies. Wilson[18] and Feldmann[19] also recommend certain land lengths. Sieber[20] suggests that in axisymmetric extrusion, there is an optimum land length which is given by the following equation:

$$L_e = 1.2 \text{ to } .8\sqrt{d}$$

where $L_e$ = land length

$d$ = diameter at the land.

In shape extrusion, unlike in rod or tube extrusion, die land length is changed to slow down or to speed up metal flow. According to Bello,[15] with shear-faced dies, the flow can be enhanced by filing a relief bearing or can be slowed down by filing a choke surface on the die land, as seen in Figure 1-6. The shape of the extruded section can be modified by filing choke and relief on the die land, as shown in Figure 1-7. In Figure 1-7a, the metal at the outside of the right leg flows faster than that inside. Therefore, with the die-land corrections indicated in Figure 1-7b, the right leg will tend to go toward the inside. A similar but reverse situation exists in Figures 1-7b and 1-7d.

In the practical design of the die land for extrusion of aluminum shapes, the land is varied in length according to section width, in order to obtain uniformity of flow. As shown in Figure 1-8, the thin section is provided with less land than the thicker section.[21] An empirical guideline is to keep the land length equal to 1 to 2 times the section thickness.[16] Another empirical relation, proposed by Matveev and Zhuravski,[22] is to make the effective length of the die land, at the various portions of the die opening profile, inversely proportional to the specific perimeters of these

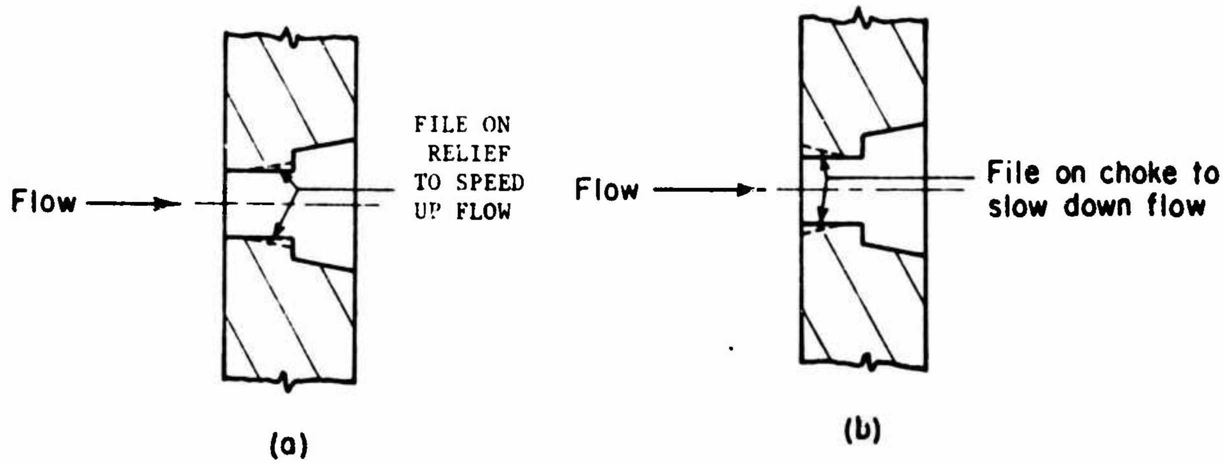



FIGURE 1-6. CORRECTION OF DIE LAND BY FILING ON RELIEF OR CHOKE[15]

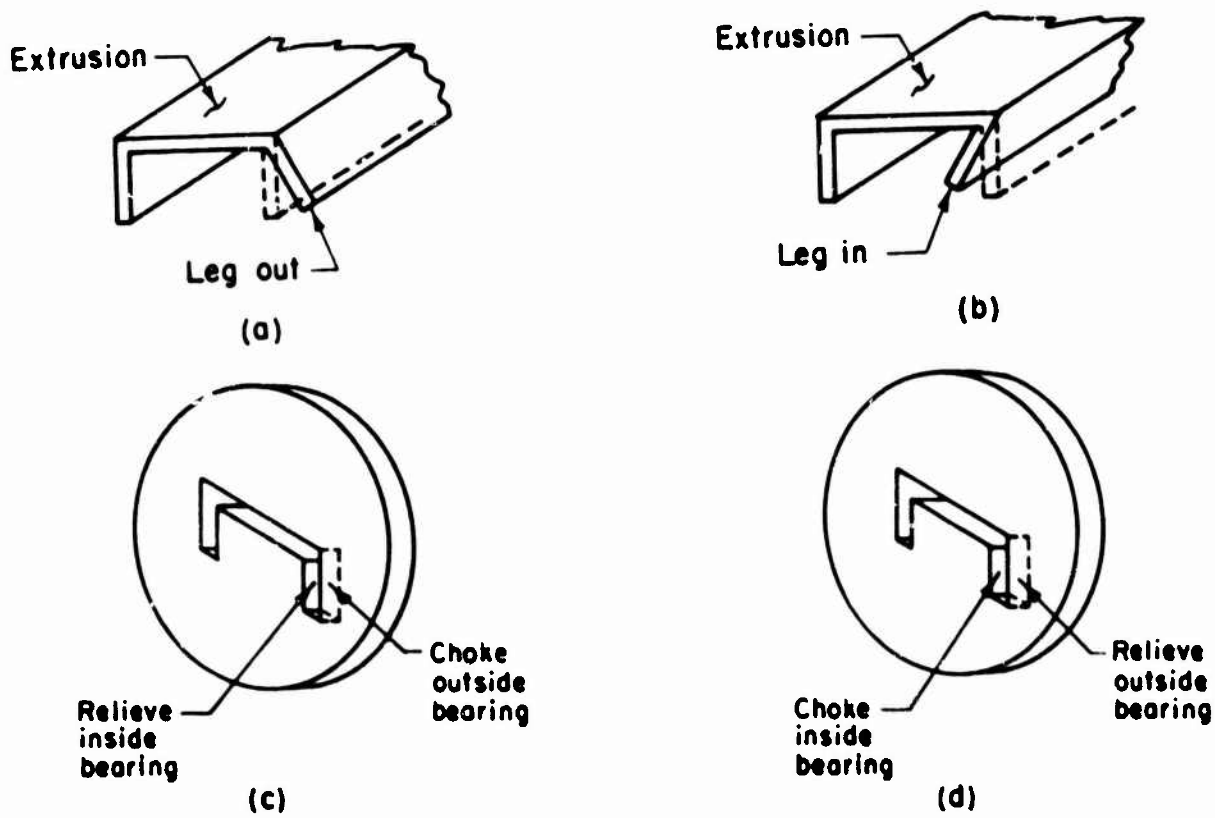



FIGURE 1-7. CORRECTION OF THE EXTRUSION PROFILE BY FILING RELIEF AND CHOKE[15]

portions:

$$\frac{l_m}{l_n} = \frac{p_{sn}}{p_{sm}}$$

$$\text{with} \quad p_{sm} = \frac{P_m}{A_m} \tag{1-1}$$

$$\text{and} \quad p_{sn} = \frac{P_n}{A_n} \quad ,$$

where $l_m$, $P_m$, $A_m$, $p_{sm}$ = effective land length, perimeter, cross-sectional area, and specific perimeter, respectively, of the portion "m" in the die profile.

$l_n$, $P_n$, $A_n$, $p_{sn}$ = effective land length, perimeter, cross-sectional area, and specific perimeter, respectively, of portion "n" of the die profile.

"m" and "n" are any two portions of the die profile which have different cross-sectional thicknesses. When die land length is assigned to a specific portion of the profile, the land length at other portions of the profile can be determined by using the relation (1-1).

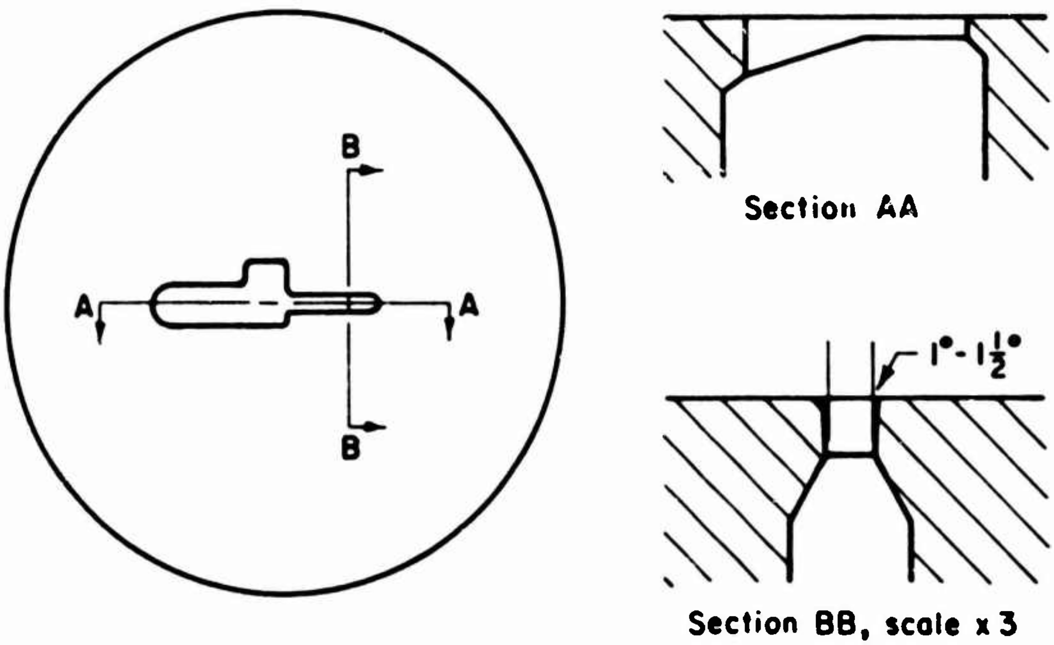



FIGURE 1-8. VARIATION OF DIE LAND LENGTH WITH SECTION THICKNESS[21]

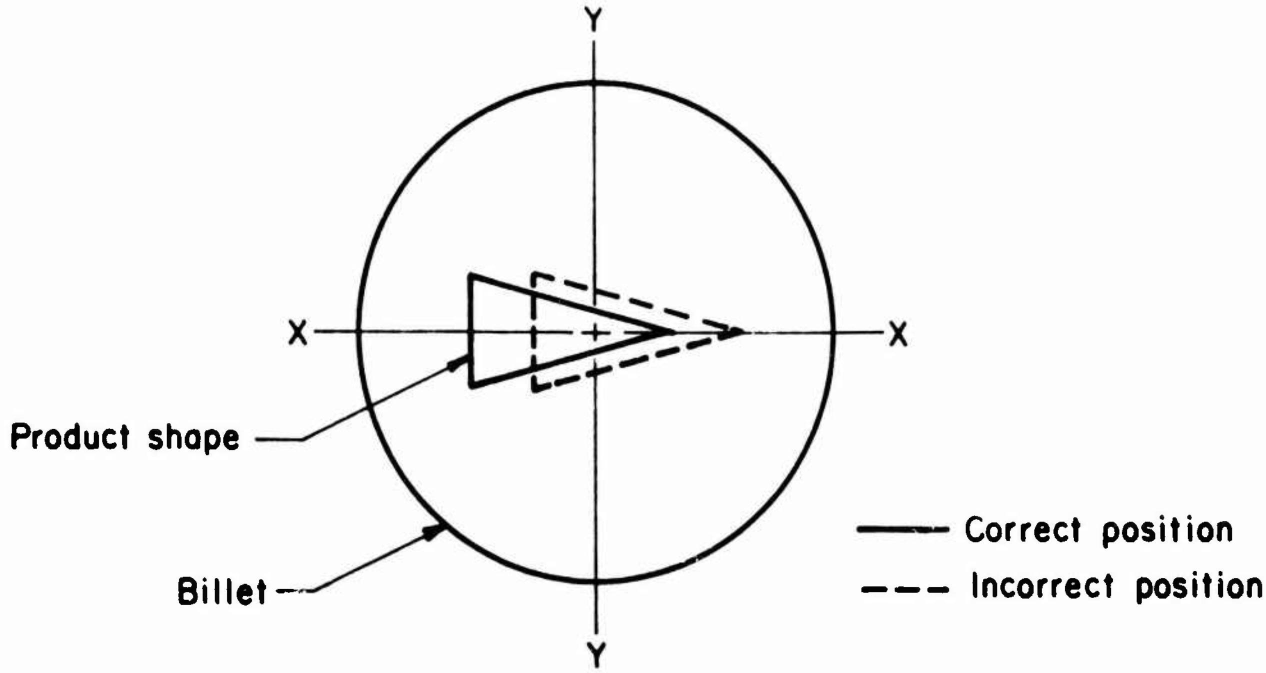
As suggested by Perlin,[22] the relation (1-1) cannot be true for all shapes, because it does not take into account the position of the die opening with respect to the center of the billet. Moreover, the determination of the specific perimeters is often arbitrary. However, this relation may be used as a first approximation in extruding shapes for which the center of gravity of the profile can be made to coincide with the center of the billet.[22]

Analytically, die-land design for extruding shapes has not been treated extensively. The only treatment is due to Scrutton, et al.,[23] who proposed criteria for die-land design, based on the distribution of temperature and metal flow in extrusion. According to these authors, the local length of the die land depends on the reduction, considered in a radial plane, for any given extrusion shape through shear-faced dies. Their work, however, is based on many assumptions which are questionable. More theoretical and experimental effort is needed to provide a scientific basis for die-land design.

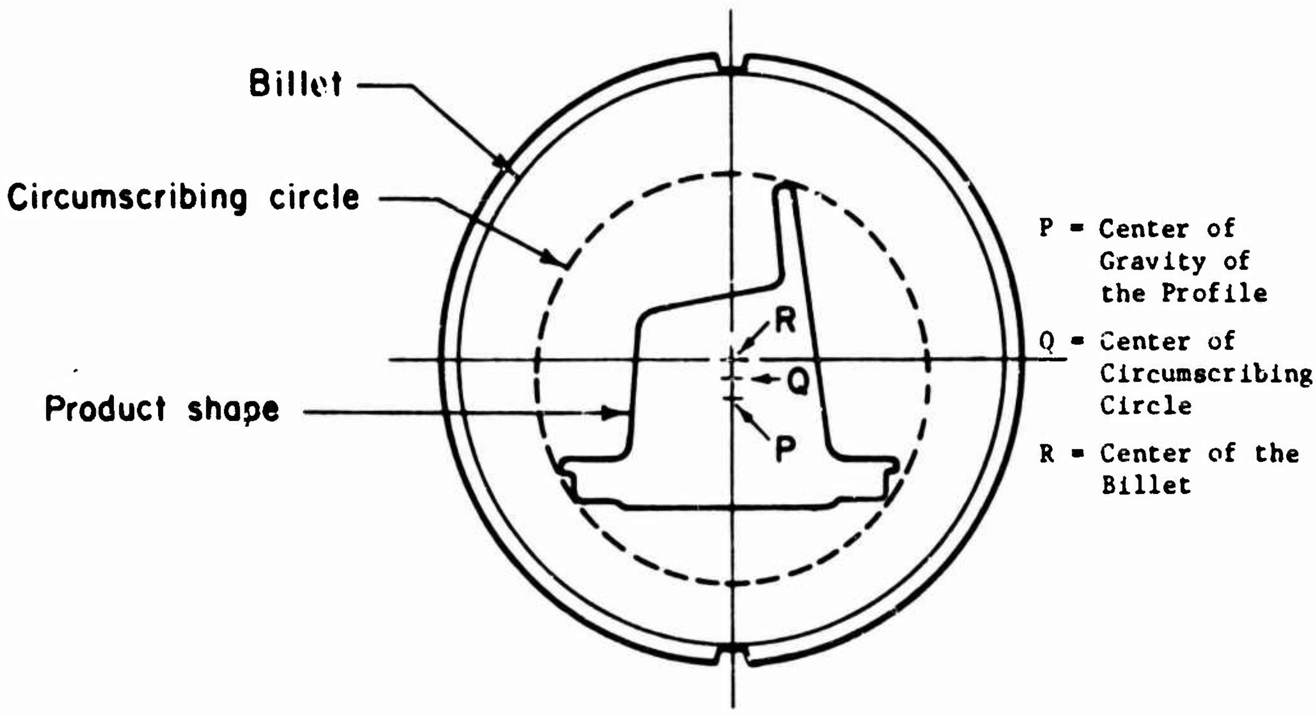
## Position of Die Profile with Respect to Billet Center

The metal flow through the extrusion die can be controlled, to a certain extent, by die-land design. Another way of equalizing the metal flow through the die is by proper positioning of the die opening, or profile, with respect to the center of the billet. The position of the die opening is affected by two main considerations:

(1) The metal near the extrusion axis tends to flow faster than the metal located near the die and container walls, due to friction at these surfaces. Thus, thinner portions of the shape, with larger specific perimeters, are usually moved towards the center, in designing the die. Figure 1-9a shows the correct positioning of a die opening with respect to billet center.[22]




(a) Correct and Incorrect Positioning of Die Opening[22]




(b) Relative Positioning of Center of Gravity of the Shape, Circumscribed Circle, and Billet

FIGURE 1-9. EXAMPLES FOR POSITIONING THE DIE OPENING WITH RESPECT TO BILLET AXIS[22]

(2) The rate of metal flow in any segment of the extruded profile can be reduced by "starving" that portion, or increased by "feeding" more material to that portion. "Starving" is done by placing the die opening such that less billet material would flow into the "starved" portion of the die opening. The opposite is done for "feeding".

Perlin[22] has suggested an empirical approach for positioning the die opening with respect to billet axis, R. According to this approach, the center of gravity of the cross section of the extruded profile, P, and the center, Q, of its circumscribing circle are determined, as seen in Figure 1-9b. If both these points, P and Q, coincide, or are very close to each other, then one of these points is made to coincide with the center of the billet, R. If Q and P are at a large distance from each other, then the center of the circumscribing circle, Q, is displaced from the center of the billet, R, in a direction towards the center of gravity, P. By this approach, the portion of the profile with smaller cross-sectional area will be opposite the portion of the billet with larger cross-sectional area, and vice versa.

In addition to the die-land design and the positioning of the extrusion profile with respect to billet axis, the die design is also affected by the billet material and the geometry and tolerances of the extruded shape.[22,24]

## The Characterization of Extruded Shapes

The aluminum industry has established certain accepted methods of characterizing extruded shapes, according to their complexity.[25] A brief review of these methods is presented below.

### Size of an Extruded Shape

The size of an extruded shape is measured by the diameter of the circle circumscribing the cross section of the shape, as shown in Figure 1-10. This is commonly referred to as CCD (Circumscribing Circle Diameter).

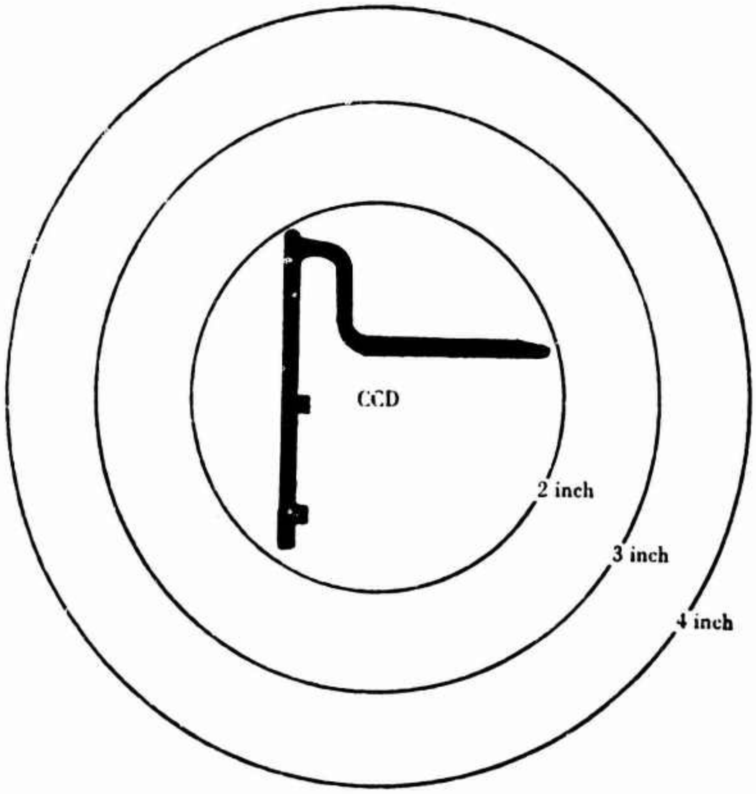



FIGURE 1-10. DEFINITION OF SIZE BY CIRCUMSCRIBING CIRCLE DIAMETER (CCD)[25]

In extrusion, metal tends to flow slower at die locations which are far away from the axis of the billet. Therefore, the larger the CCD of a shape is, the more control is required to maintain the dimensions of the extruded shape. Special care is needed in extruding large and thin shapes, and especially with thin portions of a shape near the periphery of the die. Thus, size is one of the factors describing the complexity of a shape.

## Complexity of an Extruded Shape

There are two accepted methods for defining the complexity of an extruded shape. One method is by the use of the shape factor, defined as follows:

$$\text{Shape Factor} = \frac{\text{Perimeter in inches}}{\text{Weight in pounds per foot}} = \frac{\text{Perimeter in inches}}{\text{Cross-section area in inches}^2 \times 1.2} \qquad (1\text{-}2)$$

This factor is a measure of the amount of surface that is generated per pound of metal extruded. The shape factor affects the production rate and the cost of manufacturing and maintaining the dies. It is used by many extruders as a basis for pricing and gives the designer a means of comparing the relative complexity of alternate designs.

The other measure of shape complexity is the classification of the extruded shapes into different groups, based on the difficulty in extruding them.

## Shape Classification

According to this classification, extruded shapes are divided into the following three major groups:[25]

(1) Solid shapes

(2) Hollow shapes

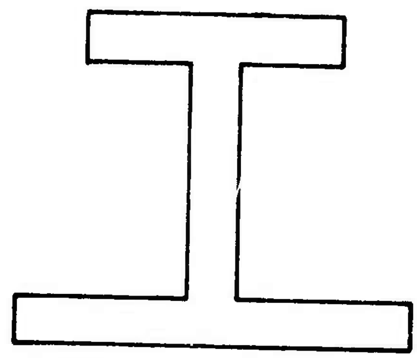
(3) Semi-hollow shapes, an intermediate group between "pure" solids and hollows.

A simple example for each of these three groups is given in Figure 1-11.

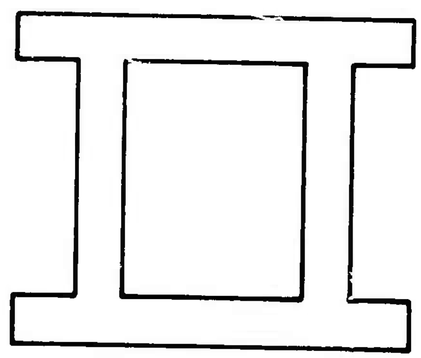
## Characterization of Extruded Shapes Used in Military Aircraft Applications

Structural shapes used in the aircraft industry are usually extruded from high-strength aluminum alloys, 2000 and 7000 series, and have usually L, I, T, U, or H type cross sections. Some extruded shapes from 2024 and 7075 aluminum alloys, which are used in military aircraft, are given in Figure 1-12. These shapes are only representative examples of many other structural extrusions used in military airplanes and helicopters.

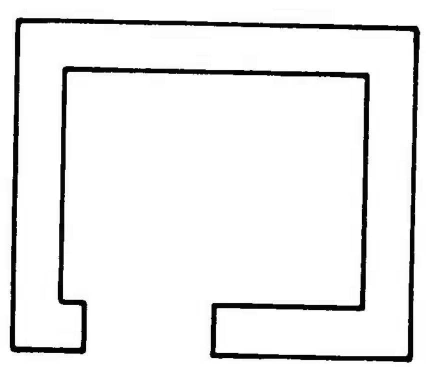
All the shapes shown in Figure 1-12 can be visualized as being made up of rectangular blocks. Thus, it should be possible to treat these shapes with the help of a rectangular module. This point is discussed later in this report.



(a) Solid Extruded Shape

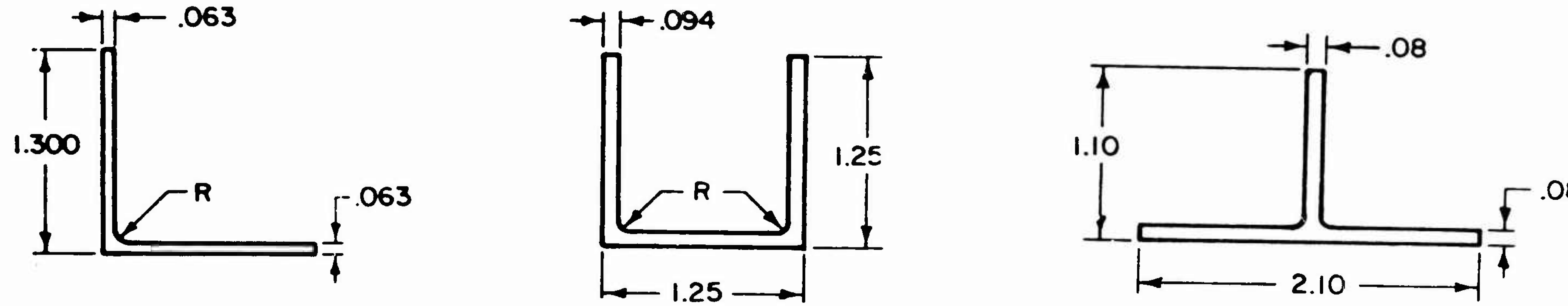


(b) Hollow Extruded Shape



(c) Semihollow Extruded Shape

FIGURE 1-11. CLASSIFICATION OF SHAPES INTO VARIOUS GROUPS[25]

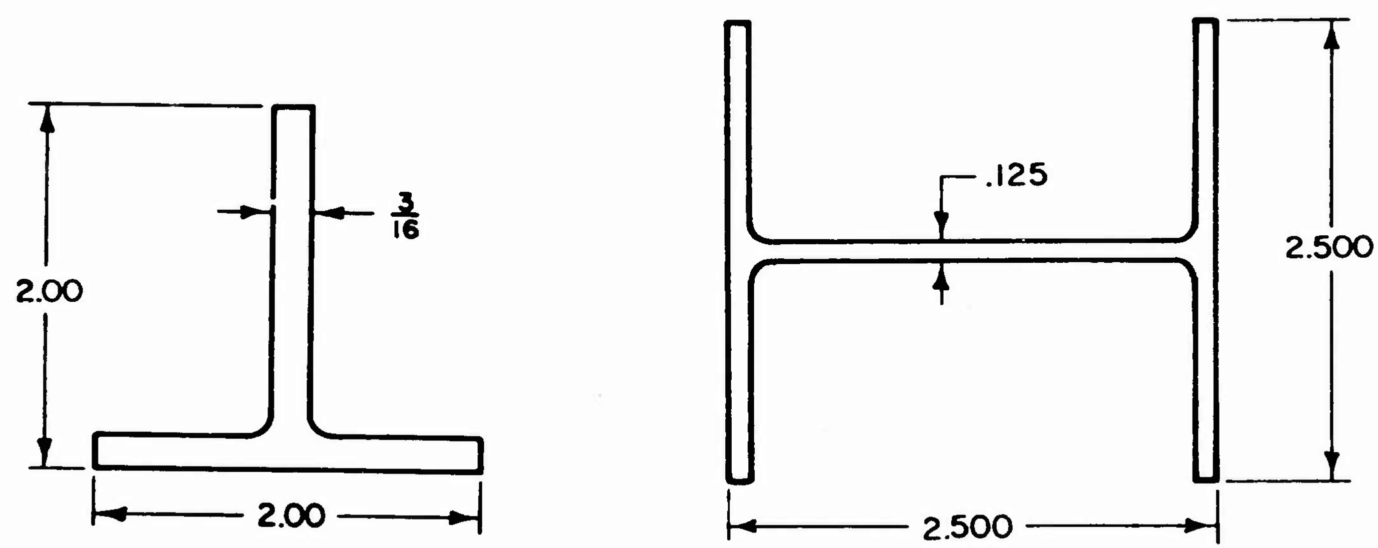



Material 7075-T6

Material 7075-T3

Material 7075-0

(a) Structural Shapes in Planes (Fillet Radius = 0.125, Corner Radius = 0.016)




Material 2024

Material 7075-T6

(b) Structural Shapes in Helicopters

FIGURE 1-12. STRUCTURAL SHAPES COMMONLY USED IN MILITARY AIRCRAFT (All Dimensions are in Inches)

Lubricated Extrusion of Aluminum Alloys

As stated earlier, the standard practice for the hot extrusion of aluminum alloys has long been to use shear-faced dies without lubrication. With this technique, the metal flows by internal shear and not by sliding along the die surface. Thus, the resulting extrusion has a high-quality finish that requires no subsequent major surface conditioning. However, this type of extrusion operation has the following disadvantages:

(1) Due to nonuniform metal flow, the redundant work and the extrusion pressure are high.

(2) The redundant work causes heat generation which, combined with the already high temperature necessary for extrusion, can cause ruptures on the surface of the extrusion, and even local melting in the extruded material. To overcome this problem, extrusion is performed at slow speeds, which reduces the production rate.

(3) Nonuniform metal flow results in anisotropy across the section of the extruded material.

Compared to using shear-faced dies without lubrication, using streamlined dies with lubrication has the advantage of providing uniform metal flow. The advantages of uniform metal flow are:

(1) Redundant work is minimized and with low friction, pressures required to extrude the alloy are reduced.

(2) Deformation heating due to redundant work is minimized so that higher extrusion speeds are possible.

(3) Uniform deformation of the cross section improves the uniformity of mechanical properties in the extruded product.

Little work has been done concerning the lubricated extrusion of aluminum alloys. Nevertheless, a few articles have been published which deserve discussion. According to Akeret,[26] by adequate lubrication of the billet and of the container, the metal flow during extrusion can be changed to such an extent that it would correspond essentially to that found in cold

extrusion. The key, of course, is the proper lubrication. Inadequate, or excessive lubrication leads to characteristic surface defects. Tool design and surface finish become important since these variables influence the effectiveness of the lubricant.

The article by Chadwick[5] seems to suggest that lubricated extrusion of aluminum will never be practical. This statement appears to be true where a plane shear-faced die is used. Work at Battelle,[27] using a conical flat die, shown in Figure 1-13, has shown interesting and promising results. Studies conducted with 2024 alloy, a hard aluminum alloy, showed that rounds and L-sections could be extruded at exit speeds over 100 ft/minute without surface cracking at a billet temperature of only 550 F. It should be noted that these exit speeds are approximately 5-10 times the exit speeds encountered in conventional extrusion. This study showed that surface finish improved with increasing extrusion ratio and with increasing extrusion speed. For very high exit speeds, over 200 fpm, the surface of the extruded product showed scoring. It was felt that better lubrication could improve this condition. In general, however, the quality of the extruded rods and L-sections were comparable to that of conventionally extruded material.

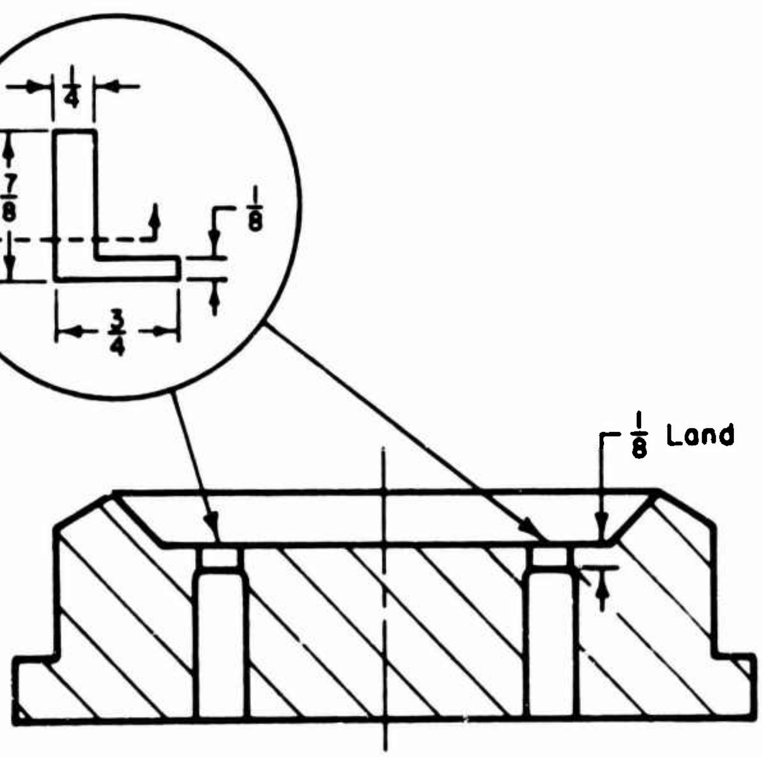



FIGURE 1-13. CONICAL-FLAT DIE DESIGN USED IN LUBRICATED EXTRUSION OF TWO L-SECTIONS FROM ALUMINUM ALLOYS[27]

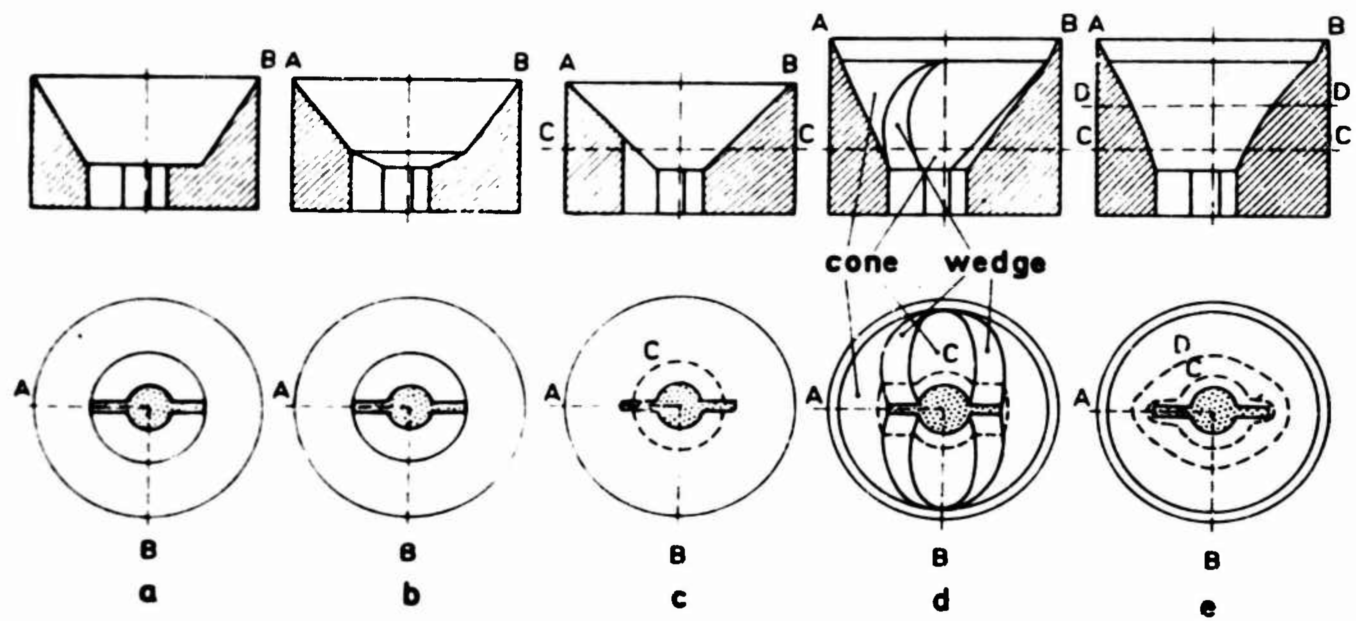
An article by V. V. Kornilov, et al.,[28] describes the experimental extrusion of fan blades from certain aluminum alloys with different lubricants. The authors concluded that chamfered billets, with either an acqueous suspension of $MoS_2$, or Cu plating (20 μm) in $CuSO_4$ and $MoS_2$ gave good results.

Ivonoff, et al.,[29] also used the lubricated-extrusion process to extrude 0.12-inch wall tubing in a 480-ton vertical press. Tubes having 29-mm OD x 23-mm ID were successfully extruded using moderate amounts of lubrication, using a conical die with 60 degree included angle and a floating mandrel. Temperatures of 460 to 480 F were used and extrusion rates of 18 to 25 meters/minute (60 to 80 fpm) were obtained.

Schey, Wallace and Kulkarni[30,31] conducted lubricated extrusions of commercially pure aluminum with the aim of simulating the hydrodynamic (thick film) lubrication behavior in extruding high-strength materials. The lubricant used in these model tests was abietic acid; only round sections were extruded with an extrusion ratio of 5:1. Conical dies with included angles of 60, 90, 120 and 180 were used. Experimental variables included extrusion temperatures, by which lubricant viscosity was controlled, extrusion speed, and a variety of secondary geometrical die variables. The results showed that reduced extrusion pressure and excellent surface finish can be achieved by obtaining an optimum lubricant film through suitable selection of experimental variables.

Lubricated extrusion of hard aluminum alloys by the hydrostatic extrusion process has been investigated by Hornmark, et al.[32] They have claimed that cold lubricated extrusion of high-strength alloys at exit speeds over 5 m/sec (about 100 times the exit speeds with conventional extrusion) is possible. For the hard 7075 aluminum alloy, extrusion ratio of 200:1 and surface finish and tolerances, comparable to those obtained in cold drawing, have been obtained.[32]

An interesting study on the adiabatic extrusion of hard aluminum alloys has been conducted by Akeret.[4] The important feature of this study is the suggested die profiles for lubricated extrusion of a bar with two ribs. These profile designs are of direct interest to the present project and are shown in Figure 1-14. Until now, no comparative studies have been published on the relative merits of these different designs, including their influence on extrusion pressure, uniformity of lubrication, and surface finish.




(a) Conical Flat (b) Double Conical (c) Conical Shape (d) Cone and Wedge (e) Streamlined

FIGURE 1-14. POSSIBLE DIE DESIGNS FOR LUBRICATED EXTRUSION OF A BAR WITH TWO RIBS(4)

It is quite evident from the present state-of-the-art survey that lubricated extrusion of aluminum alloys is possible and has a definite potential, especially when applied to the extrusion of hard aluminum alloys. As shown in Figure 1-2, the speeds used in extrusion of soft alloys is quite high. Also, the extrusion pressure, being relatively low, is not a limiting factor in the process design. This observation, coupled with the fact that flat-faced dies are more economical to manufacture than streamlined dies, seems to suggest that lubricated extrusion of soft aluminum alloys may not be economically feasible.

However, in extrusion of hard alloys, much can be gained through lubricated extrusion with streamlined dies. Higher extrusion speeds could be obtained because of smaller temperature increases due to friction and redundant work. Also, lower capacity presses could be used since the required specific extrusion pressures would be less in lubricated extrusion through streamlined dies than in nonlubricated extrusion through flat-faced dies.

## EXTRUSION OF SHAPES FROM STEEL AND TITANIUM ALLOYS

Titanium alloys, alloy steels, stainless steels and tool steels are extruded on a commercial basis, using a variety of graphite and glass base lubricants. Commercial grease mixtures containing solid-film lubricants, such as graphite, often provide little or no thermal protection to the die; therefore, die wear in conventional extrusion of steels and titanium alloys is very significant and results in high costs.[2] Efforts are being concentrated on improving the manufacturing technology of extrusion tooling.[34,35] Studies at TRW[36] have demonstrated that a mixture of magnesium metaborate and graphite in water shows considerable promise as an extrusion lubricant at temperatures as high as 3500 F. With this lubricant, 4340 steel "T" sections were extruded at 1800 F, and Mo-0.5Ti "T" sections were extruded at 3500 F. Surface finishes were good in both instances.[36]

## The Séjournet Process

In the Séjournet process, the heated billet is commonly rolled over a bed of ground glass, or it is sprinkled with glass powder which supplies a layer of low-melting glass to the billet surface.[33,37] Prior to insertion of the billet into the hot-extrusion container, a suitable die glass lubricating system is positioned immediately ahead of the die. This may consist of a compacted glass pad, glass wool, or both. The prelubricated billet is quickly inserted into the container followed by appropriate followers or a dummy block, and extrusion cycle is started, as seen in Figure 1-15.[1]

The unique features of glass as a lubricant are its ability to soften selectively during contact with the hot billet and, at the same time, to insulate the hot-billet material from the tooling, which is usually maintained at a temperature considerably lower than that of the billet. In extruding titanium and steel, billet temperature is usually 1800 F to 2300 F whereas the maximum temperature which tooling can withstand is 900 to 1000 F. Thus, the only way to obtain compatibility between the very hot billet and considerably cooler tooling is to use appropriate lubricants, insulative die coating and ceramic die inserts, and to design dies to minimize tool wear. To date, only glass lubricant has worked successfully on a production basis in extruding long lengths.

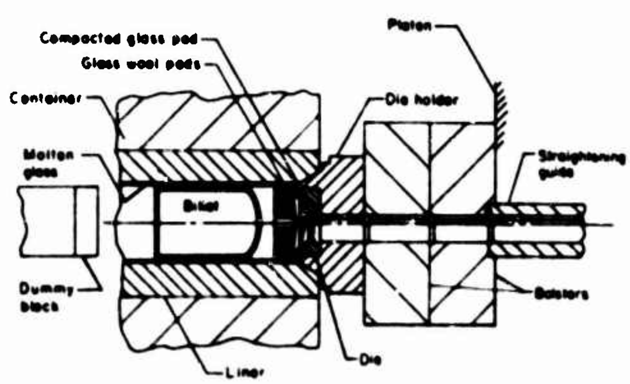



**FIGURE 1-15. HOT EXTRUSION SETUP USING GLASS LUBRICATION[1]**

## Extrusion Speed

The actual ram speed attainable during extrusion varies with alloy composition, extrusion temperature, and extrusion ratio, but is usually in the range of 200 to 300 in/min. High-extrusion speeds are preferred whether grease or glass is used as lubricant. As grease lubricants offer little protection from the high-extrusion temperatures, the hot billet should be in contact with the die for as short a time as possible. With glass acting as an insulator between billet and tools, this problem is somewhat reduced. However, the basic principle of glass lubrication, i.e., glass in a state of incipient fusion flowing continuously from a reservoir, requires high-extrusion speeds. With low speeds, the glass reservoir may be depleted before completion of the extrusion stroke, since the melting rate of the glass is a function of time.

## Die Design

Two basic types of metal flow occur during extrusion of titanium and steel with lubrication:

(1) Parallel metal flow in which the surface skin of the billet becomes the surface skin of the extrusion

(2) Shear metal flow in which the surface skin of the billet penetrates into the mass of the billet and creates a stagnant zone of metal at the die shoulder which is retained in the container as discard. Shear flow is undesirable because it prevents effective lubrication of the die and can cause interior laminations and surface defects in the extruded product.

In extrusion with grease lubricants, the common practice is to use modified flat-faced dies having a small angle and a radiused die entry. In the glass-extrusion process, the die must be designed not only to produce parallel metal flow, but also provide a reservoir of glass on the die face. The general design employed by companies licensed for the process is a flat-faced design with a radiused entry into the die opening. During extrusion, the combination of the glass pad on the die and the uniform metal flow produces a nearly conical metal flow towards the die opening.

In a study conducted by the Republic Aviation Corporation,[38] extrusion trials were performed on titanium alloys C-135 AMo and MS 821 to extrude L shapes, i.e., angles. Both glass lubricants and grease and graphite lubricants were investigated. Glass lubrication resulted in better surface finish and die life. The major problem with grease and graphite was maintaining sufficient lubrication over the full length of the extrusion. A multi-hole die, flat die with 20 degree inlet angle, seen in Figure 1-16, produced good results.

In the same study,[38] extrusion trials were conducted at U.S. Steel to extrude small U-shaped channels from titanium alloys. The conclusion of this study was that conical dies had no noticeable advantage over flat-faced dies when glass lubrication was used during the extrusion. Laminar flow was obtained with both die types. A disadvantage of conical dies with glass lubrication was the loss of much of the glass pad with the first foot of extrusion. When grease-based lubrication was used, shear-type flow occurred with both conical and flat-faced die types, but the shear cone formed was somewhat less pronounced with a conical die contour. The flat-faced die used in this study is shown in Figure 1-16. Similar conclusions were made based on extrusion trials at H. M. Harper Company.[38] Conical dies enhanced the metal flow, but did not retain the glass for proper lubrication. In final trials at Babcock and Wilcox Corporation, a modified flat-faced die was successfully employed for T-shape extrusion. The die is shown in Figure 1-17.

Similar die designs were used for extruding T shapes of Beta III and other titanium alloys with glass lubrication.[39-41] In the Sejournet process, it is usually assumed that the primary function of the die-glass pad is to lubricate the die. In a study conducted by Northrop and Harper[42] on extruding "T" sections of steel, it was determined that the glass pad placed in front of the die does not lubricate the surface of the extrusion and is not necessary to produce an acceptable surface finish. The function of the die-glass pad is to provide a smooth flow pattern for the billet material. If that is the case, then better extrusions may be obtained by streamlined dies, even without a glass pad. The die used in Harper's study was quite similar to that shown in Figure 1-17. It is interesting to note that in the optimized die-glass pad design, the amount of glass used is very

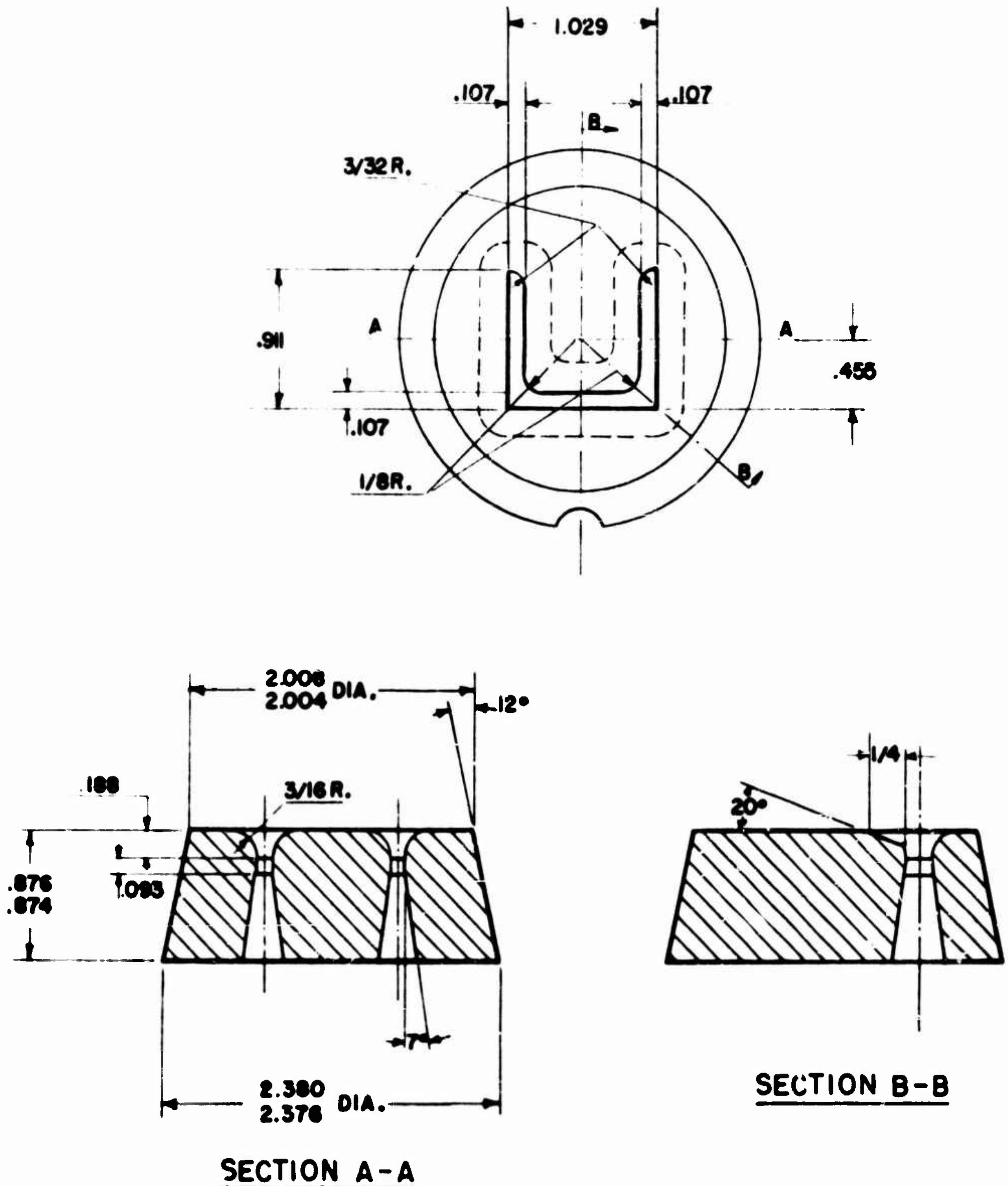
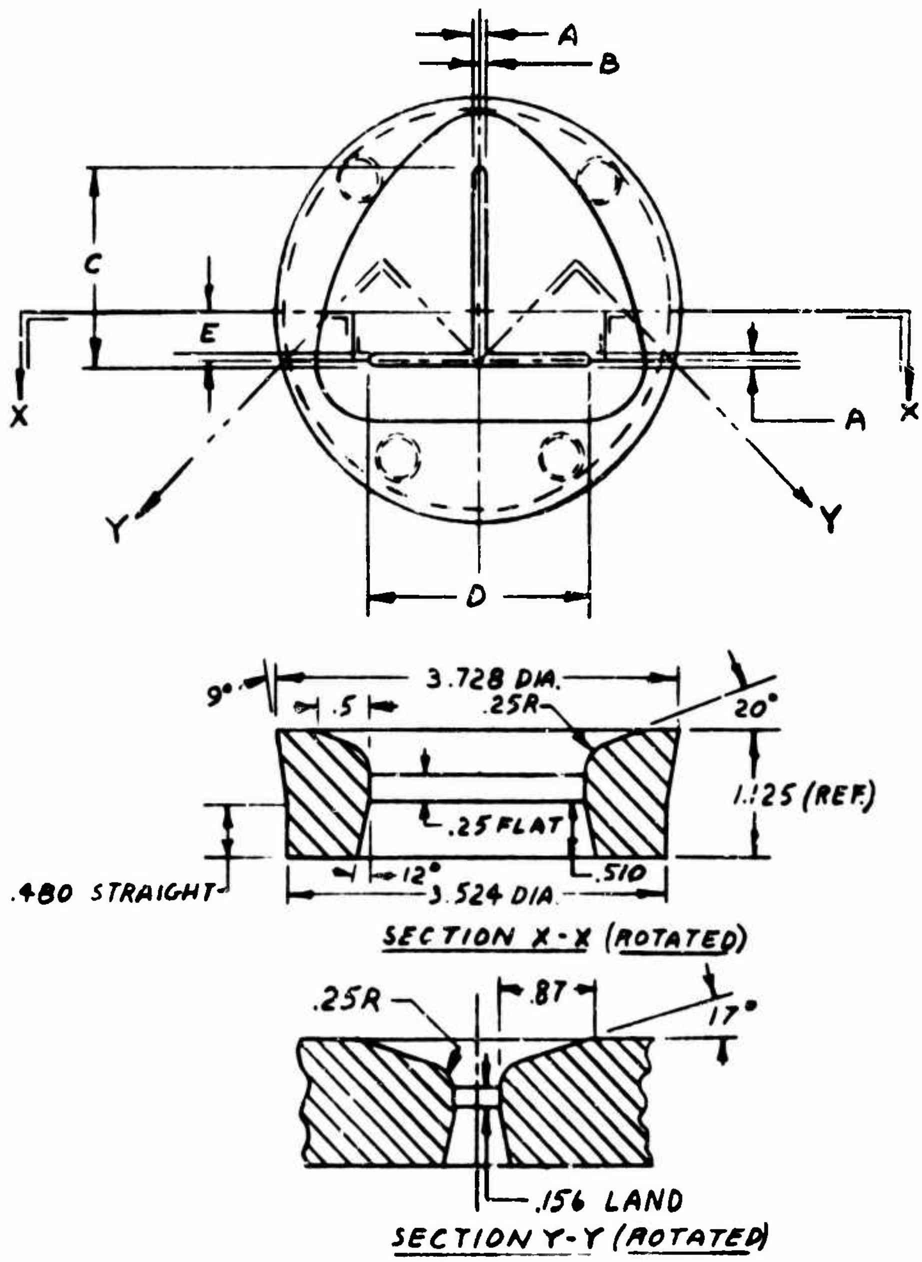



FIGURE 1-16. FLAT-FACED DIE USED FOR EXTRUDING TITANIUM ALLOYS Ti-155A AND C135 AMo (38)




| SHAPE* | A | B | C | D | E |
|---|---|---|---|---|---|
| 676 | .063 | .0315 | 1.685 | 1.840 | .410 |
| 676A | .072 | .036 | 1.685 | 1.840 | .410 |
| 677 | .098 | .049 | 1.050 | 1.840 | .175 |

FIGURE 1-17. MODIFIED FLAT-FACED DIE DESIGN USED FOR EXTRUDING TITANIUM ALLOYS WITH GLASS LUBRICANT(38)

much reduced and the design of the shape of the glass pad is primarily for providing streamlined flow.[42] In another study on extrusion of steel, die design, similar to that shown in Figure 1-17, was used.[43]

An interesting conclusion was made in a study on the extrusion of Beryllium.[44] In this study, it was determined that flat-faced dies are best for the glass lubricant approach, i.e., Sejournet process, but dies with conical entry are best suited for using composite lubricants having metallic and non-glass liquid components. Based on several extrusion trials, a conical entry die was selected to encourage smooth metal flow. The dies were cast by the Shaw process by "Duplicast Die Company of Detroit" and were finished at the "Moczik Tool and Die Company, Detroit". Of special importance to our project is their conclusion quoted here. "It was apparent from past experience that the die design would have to be altered radically because of the complete change in type and method of application of lubricants. Under the Sejournet system of glass lubrication, flat-faced design was a necessity to provide the reservoir of semi-molten glass which was gradually drawn off as the billet passed the so-called "dead zone". With the composite lubricant technique in which the beryllium never touches the die, the metallic and liquid lubricants are applied over the entire billet surface prior to insertion into the container. This obviates the need of the reservoir provided by flat-faced dies and, in fact, dictates the need for smoother, more streamlined flow". This was accomplished best by using a conical die approach. In the study with glass lubrication, conical contour dies with varying geometries were tried. With dual lubricant systems, a curved die, as shown in Figure 1-18, was used.

The above conclusion does not seem to apply to all situations. In extruding complex thin H-sections of Tantalum alloy,[45] better and more consistent results were obtained with the conical H-dies than the modified flat dies. Conical dies have also been used in glass-lubricated extrusion of T shapes from TZM alloy,[46] as shown in Figure 1-19.

The review of past studies show that, basically, two types of dies are used for extruding steel and titanium: (a) flat-faced die, or modified flat-faced die with radiused entry, and (b) conical entry die. It seems that flat-faced dies, or modified flat-face dies are used with glass lubrication with glass pad forming the die contour at the entrance. The conical entry

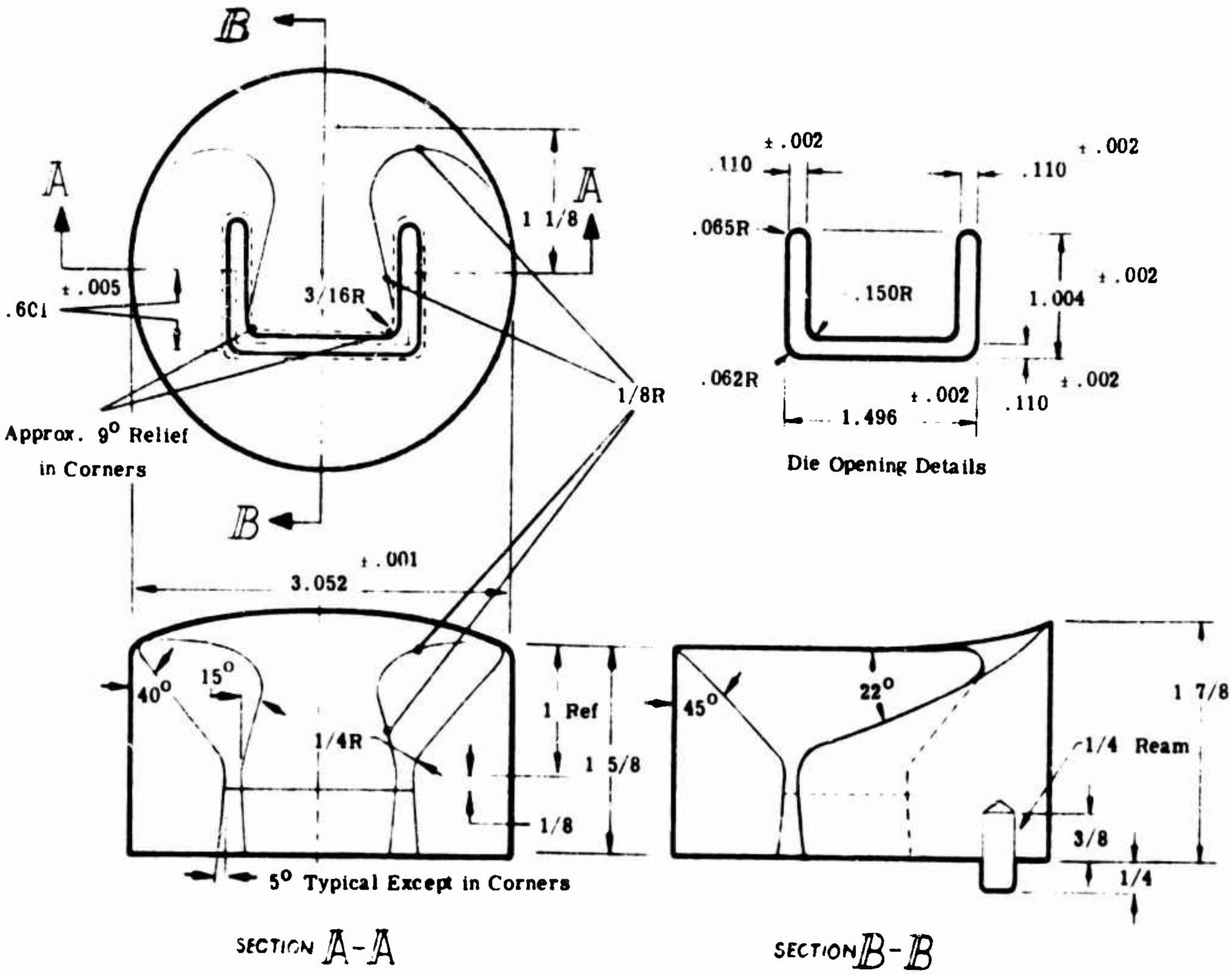



FIGURE 1-18. CURVED DIE USED FOR EXTRUDING BERYLLIUM(44)

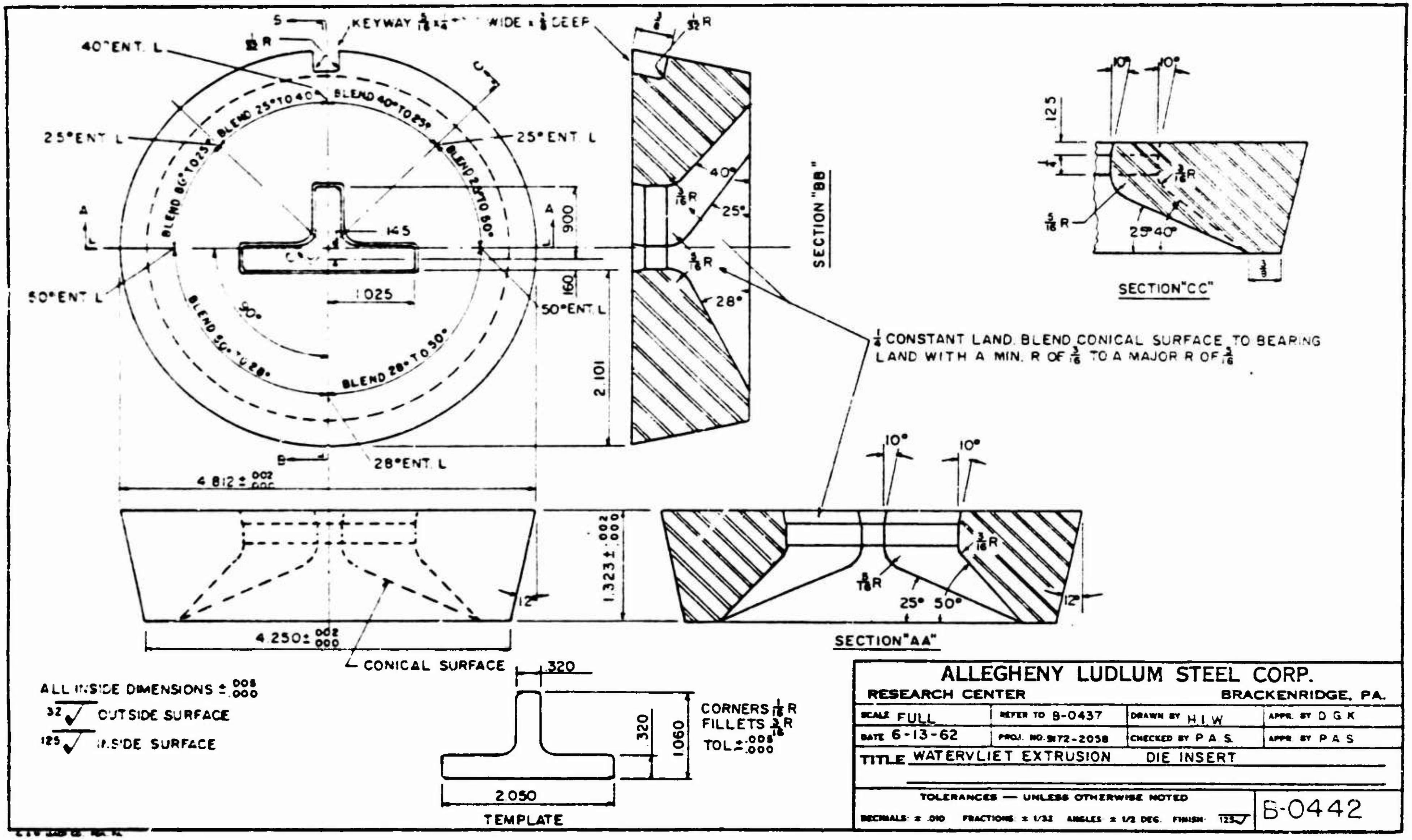



FIGURE 1-19. CONICAL DIE USED FOR EXTRUDING TZM "T" SHAPES(46)

die is mostly used with grease lubrication, although there is evidence, at least in extrusion of other high-strength alloys, that conical-contoured dies are also used with glass lubrication. From the review, it is obvious that in designing dies for lubricated extrusion, an important consideration, in addition to uniform flow, is the uniform distribution of lubricant on the surface of the billet.

## DESIGN OF STREAMLINED DIES IN SHAPE EXTRUSION

From the present review, it is quite apparent that die design in shape extrusion is quite complex and it is influenced by a variety of factors, such as the type of extrusion process, (direct, indirect, or hydrostatic), the material to be extruded, (aluminum, steel, or titanium), extrusion temperature and pressure, lubrication (unlubricated, glass lubrication, or grease lubrication), and the desired shape of the product. Other factors that will influence die design are billet size, press capacity, extrusion ratio, number of cavities in die, press-tool arrangement, and die materials.

No single die design can be used for all possible extrusion conditions. Thus, it may be advisable to suggest alternative die designs for the following types of extrusions:

(1) Materials hot extruded in a direct process with glass lubrication, glass pad being used between the billet and the die. This group includes the extrusion of steels, titanium alloys, and high-temperature alloys.

(2) Materials hot extruded in a direct process with grease or oil type lubricants, including hard aluminum alloys.

(3) Materials that can be more economically extruded through shear-faced dies without lubrication. Soft aluminum alloys would fall in this category where calculation of extrusion pressure and design of die land to give uniform flow are two areas requiring engineering improvements.

(4) Materials extruded by hydrostatic extrusion process.

(5) Shapes too complex to be extruded by a single contoured die. This group may include aluminum alloys that are usually extruded to complex shapes through bridge or porthole dies.

The possible die designs feasible with the streamlined die design approach are shown in Figure 1-20, along with the applications for which these may be suitable. It is advisable to omit group (5) above altogether, and also not to propose lubricated extrusion of soft aluminum alloys since this may not be economically feasible.

In all the die designs of Figure 1-20, except in the flat-faced die, Figure 1-20d, the die surface provides a smooth transition from the billet shape to the required final shape. The final shape of the transition zone can be the product shape, or some other defined shape surrounding the die opening, as seen for the curved-flat die in Figure 1-20b. In all cases, the die surface must be defined and optimized taking into account the variables of the extrusion process.

All the shapes like L, T, U, and H, used for military applications, can be represented by assembling rectangles of different sizes having different amount of offset from the billet axis. This suggests that a basic rectangle, positioned off-center from the billet axis, can serve as a module for the purpose of defining the streamlined die surface and for analyzing metal flow.

## SUMMARY

This chapter presents a survey of the present state of the art in die design, as related to extrusion of shapes from aluminum alloys, steels, and titanium alloys. The purpose of this survey was to

(1) Characterize the extruded structurals used for military aircraft applications.

(2) Assess and gather the existing literature relevant to die design in extrusion of structural shapes.

(3) Define guidelines for subsequent tasks on the current project for CAD/CAM of extrusion dies.

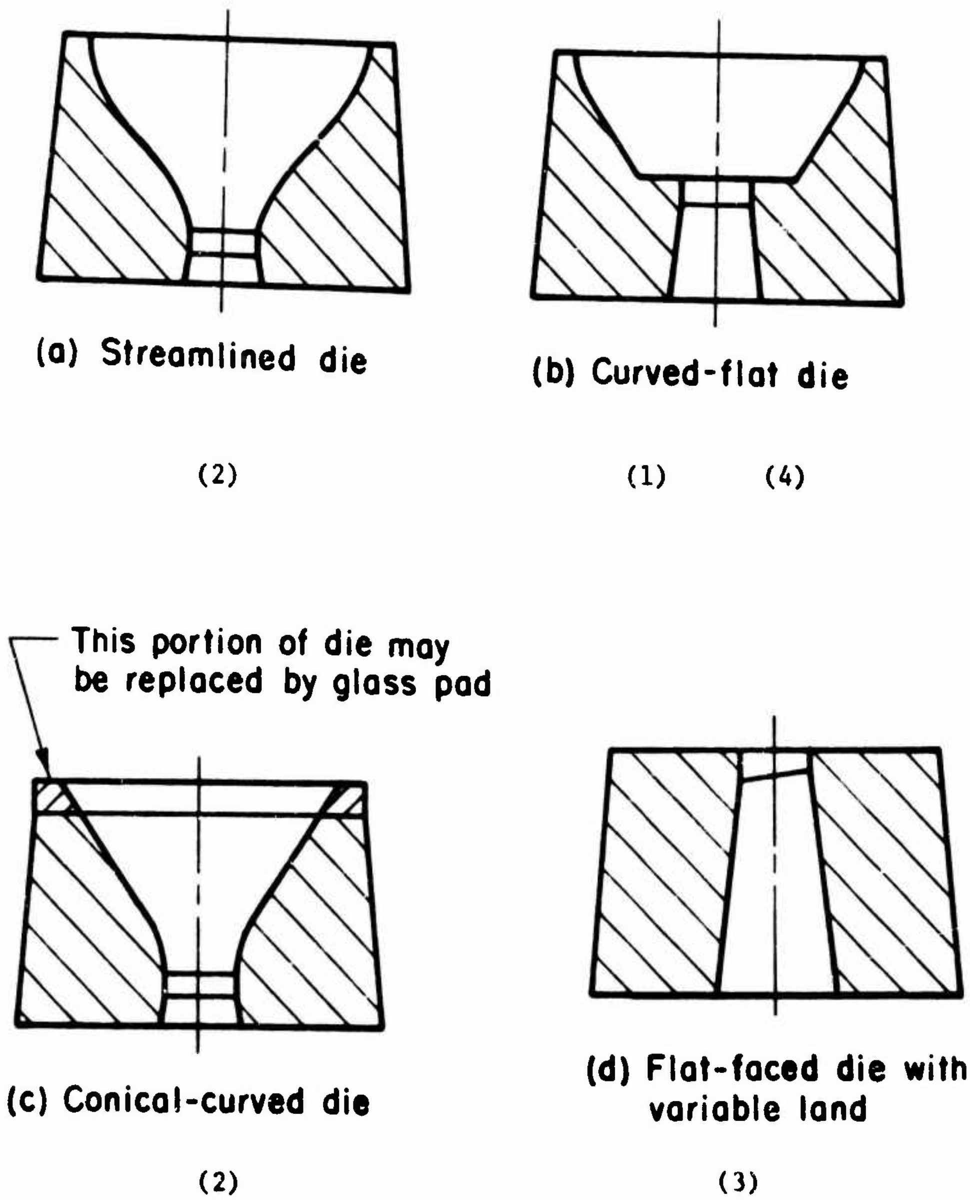



FIGURE 1-20. POSSIBLE DIE DESIGNS FOR EXTRUSION OF ALUMINUM, STEEL AND TITANIUM ALLOYS

(The Numbers Below Each Sketch Indicates the Possible Application as Described in Text)

The present chapter deals with the extrusion of aluminum alloys separately from the extrusion of steels and titanium alloys, because of the different technologies associated with extrusion of these materials. The review shows that in extrusion of aluminum alloys, flat-faced dies are used which limit the extrusion rate for the hard aluminum alloys, 2000 and 7000 series. The past work on lubricated extrusion of hard aluminum alloys suggests that it is possible to increase the extrusion rates by using the lubricated extrusion process with streamlined dies. The design of streamlined dies, and die and billet lubrication are two areas which need further investigation.

The extrusion of steels and titanium alloys is either done by the conventional direct extrusion process with grease-graphite lubricants, or more commonly by the Sejournet process with glass lubrication. In either case, the high strengths of these materials require that a smooth transition is provided in the die from the billet to the final shape. With glass lubrication, the glass pad, together with the flat-faced die, provides that transition. With grease-graphite lubricants, the die must provide a smooth change of shape and, therefore, in this case, die design becomes relatively more important than in extruding with glass.

There are many variables in the extrusion process. Therefore, one particular die design is not likely to be suitable for all situations. The structural shapes used in aircraft applications are relatively simple and can be considered as formed by assembling several rectangles in appropriate manner. Therefore, a rectangular module can serve as a basis for die design in lubricated streamlined extrusion.

# REFERENCES


(1) Byrer, T. G., et al., "Design Guide for Use of Structural Shapes in Aircraft Applications", Battelle's Columbus Laboratories, Columbus, Ohio, Technical Report AFML-TR-73-211, September, 1973.

(2) Gerds, A. F., et al., "Deformation Processing of Titanium and Its Alloys", Battelle Memorial Institute, Columbus, Ohio, NASA Technical Memorandum NASA TM X-53438, April, 1966.

(3) "Aluminum Extrusions, Fabricating and Anodizing", Booklet by Southern Extrusions, Inc., Magnolia, Arkansas.

(4) Akeret, R., and Stratman, Paul M., "Unconventional Extrusion Processes for the Harder Aluminum Alloys", Part I and II, Light Metal Age, April, 1973, pp 6-10, and June, 1973, pp 15-18.

(5) Chadwick, R., "Developments and Problems in Package Extrusion Press Design", Metals and Materials, May, 1969, pp 162-170.

(6) Akeret, R., "A Numerical Analysis of Temperature Distribution in Extrusion", J. Inst. Metals, 95, 1967, p 204.

(7) Lahoti, G. D., and Altan, T., "Prediction of Metal Flow and Temperatures in Axisymmetric Deformation Processes", presented at the 21st Sagamore Army Materials Research Conference, August 13-16, 1974, published in the Proceedings.

(8) Lahoti, G. D., and Altan, T., "Prediction of Temperature Distributions in Tube Extrusion Using a Velocity Field Without Discontinuities", Proceedings of the 2nd North American Metalworking Research Conference, Madison, Wisconsin, May, 1974, pp 209-224.

(9) T. Munker, German Patent No. 901,529, 1953.

(10) Laue, K., "Isothermal Extrusion", (in German), Z. Metallkunde, 51, 1960, p 491.

(11) Fernback, H. R., "Programmed Speed-Control Methods for Extrusion Process", J. Inst. Metals, 92, 1963-64, pp 145-148.

(12) Laturin, A. I., "Extrusion of Aluminum Alloys Through a Water-Cooled Die", (in Russian), Kuznechno-Shtampovochnoye Proizvodstvo, No. 8, 1966, pp 5-9.

(13) Aluminum, Vol. 3, Fabrication and Finishing, edited by K. R. Van Horn, American Society for Metals, Metals Park, Ohio, 1967, pp 81-132.

(14) Carl DeBuigne, "Design and Manufacture of Aluminum Extrusion Dies", Light Metal Age, 27, April, 1969, pp 28-33.

(15) Bello, Luis, Aluminum Extrusion Die Correction, First edition, Fellom Publications, San Francisco.

(16) Mockli, F., and Locher, M., "State of the Art in Making Extrusion Dies", Aluminum, (in German), 41, 1965, p 629.

(17) Keegan, J. W., "Hints in Modern Cold Heading", Automatic Machining, 28, No. 2, 1966, pp 63-66.

(18) Wilson, G., "Cold Forging", Metal Treatment, 33, No. 252, 1966, pp 345-353.

(19) Feldmann, H. D., "Cold Forging of Steel", Hutchison and Company, Ltd., 1961.

(20) Sieber, K., "Special Cold Forging Tools, Particularly for Solid Forming on Multi-Stage Transfer Presses", Wire World International, 6, No. 6, 1964, pp 165-178.

(21) Chadwick, R., "The Hot Extrusion of Nonferrous Metals", Metallurgical Reviews, 1959, 4, No. 15, pp 189-255.

(22) Perlin, I. L., Theory of Metal Extrusion, published by "Metallurgiya", Moscow, 1964 (English Translation FTD-HT-23-616-67).

(23) Scrutton, R. F., Robbins, B., and The, J. H. L., "The Exit Lands in Extrusion Die Design", (unpublished research).

(24) Heinen, B., "Manufacturing and Correction of Extrusion Dies", (in German), Z. Metallkunde, 58, 1967, p 215.

(25) Shape Design Manual- Aluminum Extrusions, Aluminum Limited, October, 1964, AIA-RAIC FILE NO. 15-L, ALCAN Aluminum Corporation, 111 West Fiftieth Street, New York, N. Y. 10020.

(26) Akeret, R., "Research in the Nonferrous Metal Product Industry, Part XX, Effects of Lubricating the Container on the Extrusion of Aluminum and Aluminum Alloys", (in German), Z. Metallkunde, 55, 10 (1964), pp 570-573.

(27) Nichols, D. E., Byrer, T. G., and Sabroff, A. M., "Lubricated Extrusion of 2024 Aluminum Alloy Using Conical and Conical-Flat Dies", Summary Report to Battelle Development Corporation, Battelle's Columbus Laboratories, Columbus, Ohio, January 23, 1970.

(28) Kornilov, V. V., Nedourov, Yu. S., Antonov, E. A., Abrosimov, A. I., and Smirnov, G. A., "Experimental Extrusion of Aluminum-Alloy Fan Blades", (in Russian), Kuznechno-Shtampovochnoye Proizvodstvo, 10, October, 1970, p 15.

(29) Ivonov, I. I., Rakhmanov, N. S., Molodchinin, E. V., Molodchinina, S. P., and Medvedeva, R. D., "Extrusion of Thin-Walled D 16 Alloy Tubes on a Vertical Press", The Soviet Journal of Nonferrous Metals, 9, (7), July, 1968, p 100.

(30) Schey, J. A., Wallace, P. W., and Kulkarni, K. M., "Thick-Film Lubrication in Hot Extrusion", U.S. Air Force Materials Laboratory, Technical Report AFML-TR-68-141, May, 1968.

(31) Wallace, P. W., Kulkarni, K. M., and Schey, J. A., "Thick-Film Lubrication in Model Extrusions with Low Extrusion Ratios", Journal of the Institute of Metals, 100, 1972, p 78.

(32) Hornmark, N., Nilsson, J. O. H., Mills, C. P., "Quintus Hydrostatic Extrusion", Metal Forming, 37, August, 1970, p 227.

(33) Sejournet, J., and Delcroix, J., "Glass Lubricant in the Extrusion of Steel", Lubrication Engineering, 11, 1955, p 389.

(34) Turner, F. S., "Manufacturing Technology for Materials, Designs and Fabrication of Extrusion Dies for Hot Extruding of Steels and Titanium Structural Sections", Allegheny Ludlum Industries, Inc., Brackenridge, Pennsylvania, Technical Report AFML-TR-73-61, 1973.

(35) Turner, F. S., "Die Materials for Hot Extruding Steel and Refractory Metals", Allegheny Ludlum Steel Corporation, Technical Report AFML-TR-68-316, October, 1968.

(36) Haverstraw, R. C., "High Temperature Extrusion Lubricants", TRW Electro-Mechanical Division of TRW, Inc., Cleveland, Ohio, Final Report, Contract No. AF 33(657)-9141, Report ML-TDR-64-256, July, 1964.

(37) Haffner, E. K. L., and Sejournet, J., "The Extrusion of Steel", Journal of the Iron and Steel Institute, June, 1960, p 145.

(38) Christiana, J. J., "Improved Methods for the Production of Titanium Alloy Extrusions", Republic Aviation Corporation, Contract AF 33(600) 34098, ASD Project: 7-556, Final Technical Engineering Report, December, 1963.

(39) Loewenstein, P., and Gorecki, T. A., "Production Techniques for Extruding and Drawing Beta III Titanium Alloy Shapes", Whittaker Corporation/Nuclear Metals Division, Technical Report AFML-TR-72-97, May, 1972.

(40) Gorecki, T. A., et al., "Production Techniques for Extruding, Drawing, and Heat Treatment of Titanium Alloys", Fairchild Hiller, Republic Aviation Division, Technical Report AFML-TR-68-349, December, 1968.

(41) Kosinski, E. J., and Loewenstein, P., "Manufacturing Methods of an Isothermal Extrusion Process to Produce 20 Foot Complex Sections", Whittaker Corporation, Concord, Massachusetts, Contract F 33(615)-70-C-1545, Interim Engineering Report No. 1, August, 1970.

(42) Scow, A. L., and Dempsey, P. E., "Production Processes for Extruding, Drawing, and Heat Treating Thin Steel Tee Sections", Technical Report AFML-TR-68-293, October, 1968.

(43) Christensen, L. M., "The Development of Improved Methods, Processes, and Techniques for Producing Steel Extrusions", Northrop Corporation, Technical Documentary Report No. ML-TDR-64-231, July, 1964.

(44) Christensen, L. M., and Wells, R. R., "Program for the Development of Extruded Beryllium Shapes", Northrop Corporation, Contract AF 33(600)-36931, ASD Technical Report 62-7-644, June, 1962.

(45) Krom, R. R., "Extruding and Drawing Tantalum Alloys to Complex Thin H-Sections", Nuclear Metals, Division of Textron, Inc., Technical Report AFML-TR-66-119.

(46) Santoli, P. A., "Molybdenum Alloy Extrusion Development Program", Allegheny Ludlum Steel Corporation, Technical Documentary Report No. ASD-TDR-63-593, May, 1963.

# CHAPTER II

# "COMPUTER-AIDED DESIGN AND MANUFACTURING (CAD/CAM) OF A STREAMLINED DIE FOR A MODULAR SHAPE"

## TABLE OF CONTENTS



## LIST OF ILLUSTRATIONS

# CHAPTER II

## CAD/CAM OF A STREAMLINED DIE FOR A MODULAR SHAPE

### ABSTRACT

This chapter describes the work conducted towards applying CAD/CAM techniques to the extrusion of a modular shape, which was selected to be an ellipse approximating a rectangle. A theoretical analysis is presented for predicting the metal flow, the extrusion pressure, and the effect of various process variables in extrusion of the selected modular shape. Based on the analysis, computer programs are developed to simulate the extrusion process. The analysis and the computer programs were used to analyze the cold extrusion of the modular shape from Al 1100. The results indicate that the predicted values agree qualitatively with the available data.

For some selected extrusion conditions, optimal die shapes were obtained using minimum extrusion pressure as the criterion. To manufacture the dies by Electrical-Discharge Machining (EDM) process, computer programs were developed for numerical control (NC) machining of the EDM electrode.

### INTRODUCTION

In today's industrial practice, a variety of shapes from aluminum alloys are extruded without lubricants by using flat-faced dies. This practice, particularly with the high-strength alloys, i.e., 2000 and 7000 series, results (a) in significant redundant work associated with internal shearing, and (b) in temperature increases within the deformation zone.[1,2] Consequently, the extrusion process requires large press loads and it must be carried out very slowly to avoid incipient melting in the extruded product.

With lubricated extrusion of aluminum alloys, it should be possible to reduce the redundant work and internal shearing in the deforming material. Thus, extrusion pressures and temperature increases are kept at a moderate level and, consequently, higher extrusion speeds can be achieved without causing hot shortness of the product. The use of lubricants in extruding aluminum alloys requires a new approach in die design. As long as the cross section of the extruded product is circular, optimum die configurations can be obtained by using one of the existing analyses. However, for extruding more complex shapes, such as U, L, T, I and others, it is necessary to provide a smooth transition from the circular container, or billet, to the shaped die exit. The effective design of such a die must ensure a smooth metal flow and consistent lubrication. At this time, there are no known methods to analyze the metal flow and to optimize die configuration for lubricated extrusion of nonsymmetric shapes.

Extrusion dies with smooth entries, from a circular cross section into an extruded shape, are also used in extrusion of steels, superalloys, and titanium alloys. A significant application is found in extrusion of preforms for forging titanium turbine and compressor blades.(3) Before forging the thin airfoil section, a round, or preferably an elliptical shaped preform is extruded from round bar stock. The shape of the preform and the surface of transition from the round to the elliptical cross section influence the subsequent forging of the blade without any defects.

The present program is primarily aimed at increasing the productivity in extrusion of high-strength aluminum alloy structural shapes, especially those from 2000 and 7000 series. However, the CAD/CAM techniques being developed in this program, with appropriate minor modifications, will be applicable to extrusion of shapes from other aluminum alloys, titanium alloys, steels, and superalloys.

## CAD/CAM OF SHAPE EXTRUSION PROCESS - A MODULAR APPROACH

Extrusion of shapes is an extremely complex deformation process from the point of view of deformation mechanics. The metal flow, the friction at the tool-material interface, and the behavior and properties of the deforming material (under the temperature, strain rate, and strain conditions of the

extrusion process) are difficult to analyze and predict. To simulate this complex extrusion process, a modular approach is proposed. In closed-die forging, CAD/CAM techniques have been successfully applied to complex shapes using a modular approach.[4]

Nearly all the structural shapes, that are used in producing military hardware, can be formed by assembling rectangles of different sizes having different amounts of offsets from the billet axis. This suggests that a basic rectangle, positioned off-center from the billet axis, can serve as a module in simulating extrusion of more complex shapes. This chapter describes the analysis and the computer simulation developed for the extrusion of an off-centered rectangular module.

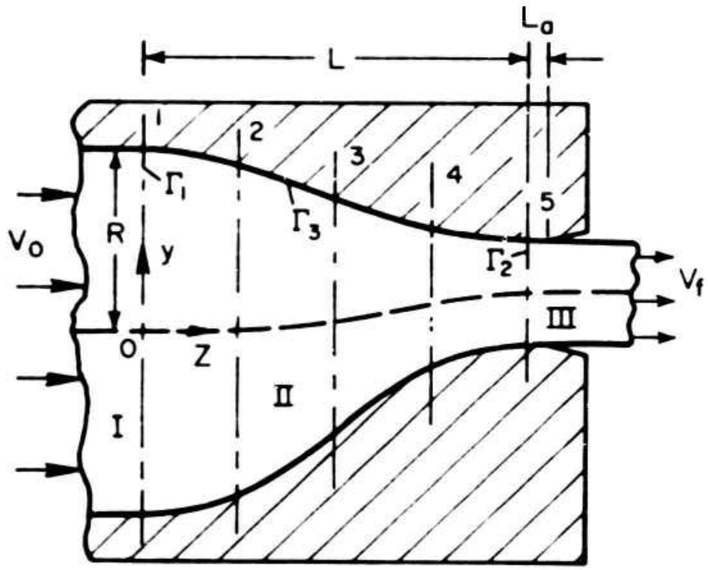
## EXTRUSION OF AN OFF-CENTERED RECTANGULAR SHAPE

A schematic of the extrusion of an off-centered rectangle from a cylindrical billet is seen in Figure 2-1. The ram pushes the billet through a die which provides a smooth change in shapes and areas of the cross sections of the workpiece. To simplify the die-surface definition and the analysis of the extrusion process, the rectangular shape is replaced by a smooth circumscribing ellipse as shown in Figure 2-1. With this approximation, the die surface can be defined analytically in a general manner as given in Appendix A. The change in shape from an ellipse to rectangle can be accomplished as a final step in machining of the extrusion die.

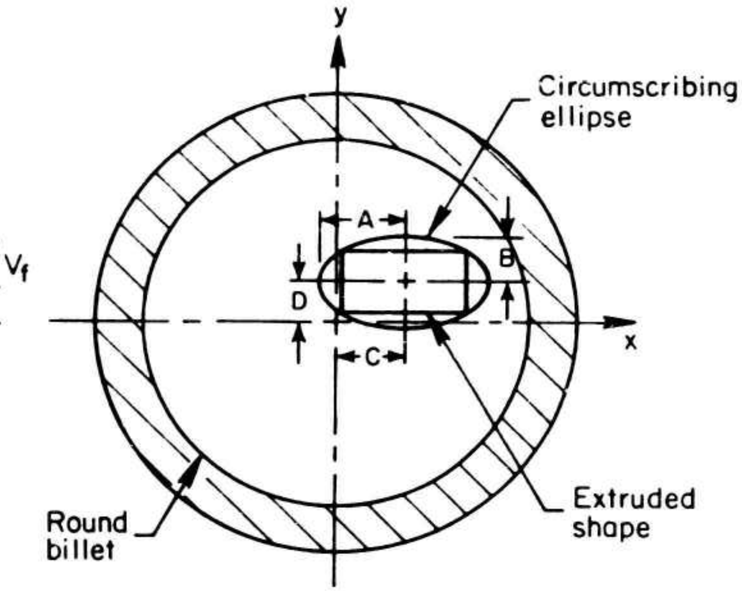
As seen in Figure 2-1, the die changes the shape of the billet cross section by successively reducing it into ellipses of different aspect ratios, A/B. Sufficient flexibility is built in the surface definition of the die so that optimal die shape may be selected later, based on the optimum metal flow.

### Analysis of Extrusion of the Elliptic Shape

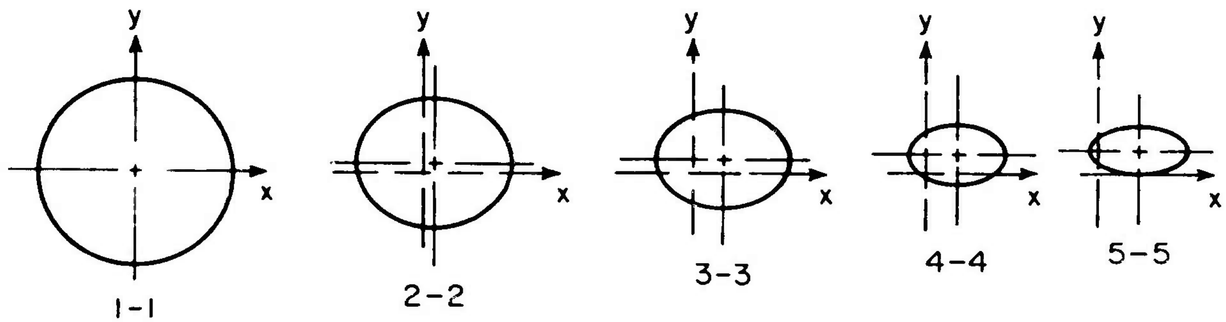
Most of the analytical studies on the mechanics of extrusion, conducted up until now, deal with two-dimensional metal flow under plane strain, or axisymmetric conditions.[5,6] However, in extrusion of nonsymmetric shapes, deformation does not necessarily occur under either plane strain or axisymmetric conditions, and no general method of solving three-dimensional forming problems has been proposed as yet.




(a) Section Through Minor Axis of the Elliptic Shape




(b) Position of the Elliptic Shape at Die Exit




(c) Cross Sections of the Billet During Extrusion

FIGURE 2-1. SCHEMATIC OF THE DIE SUGGESTED FOR LUBRICATED EXTRUSION OF AN ELLIPTIC SHAPE FROM A ROUND BILLET

In this study, the concept of dual-stream functions[7] is used to analyze three-dimensional metal flow in extrusion of elliptic shapes. Appendix A gives the details of the analysis. Basically, a kinematically admissible strain-rate field for the deformation zone is determined using dual-stream functions $\psi$ and $\chi$. An upper-bound solution is then obtained which predicts the metal flow. Extrusion pressure $\bar{P}$ is determined as function of various process variables. In functional form, $\bar{P}$ may be written as:

$$\bar{P} = \bar{P}\ (A,B,C,D,R,V_o,L_c,L,L_a,g(z),f(z),h(z),k(z),m_d,m_c,\bar{\sigma}) \qquad (2\text{-}1)$$

Some of the symbols used in the above Equation are shown in Figure 2-1. Functions g, f, h, and k define the die surface, $m_d$ is the friction shear factor over die surface, $m_c$ is the friction shear factor over container surface, $L_c$ is the length of the billet in contact with the container, $V_o$ is the billet velocity at die entrance. The flow stress of the material, $\bar{\sigma}$, is a function of strain, strain rate, and temperature at any point in the deformation zone.

Based on the analysis, computer programs were developed which simulate the extrusion of off-centered elliptic shapes. For given values of process variables, $\bar{P}$ is evaluated numerically. Appendix A gives a listing of the computer programs.

## Effect of Process Variables in Extrusion of an Elliptic Shape

A parametric study was made to determine the relation between shape change, reduction ratio, length and shape of the die, and extrusion pressure. The extrusion of a round billet into an elliptic shape, as seen in Figure 2-1, is considered. The extruded material is Al 1100 for which the flow stress is given by:[8]

$$\bar{\sigma} = 25.2\ \bar{\varepsilon}^{\ .305}\ \text{ksi for } \bar{\varepsilon} \leq 1\ . \qquad (2\text{-}2)$$

Flow stress data were not available for strains larger than $\bar{\varepsilon} = 1.0$. Therefore, it was assumed that for $\bar{\varepsilon} \geq 1$, no strain hardening takes place, i.e., $\bar{\sigma} = 25.2$ ksi. The center of the ellipse was assumed to coincide with the center of the billet. Thus,

$$C = D = h(z) = k(z) = 0\ . \qquad (2\text{-}3)$$

Also, the container surface was assumed to be frictionless, i.e., $m_c = 0$.

The functions g(z) and f(z) define the die surface. A general polynomial form for these functions was selected as follows:

$$g(z) = R + \left( C_1 L^2 - \frac{3(R-A)}{L^2} \right) z^2 + \left( \frac{2(R-A)}{L^3} - 2\ C_1 L \right) z^3 + C_1 z^4 \quad (2\text{-}4a)$$

$$f(z) = R + \left( C_3 L^2 - \frac{3(R-B)}{L^2} \right) z^2 + \left( \frac{2(R-B)}{L^3} - 2\ C_3 L \right) z^3 + C_3 z^4 \ . \quad (2\text{-}4b)$$

$C_1$ and $C_3$ are some arbitrary constants of the polynomial, describing the die surface. This polynomial form was chosen because it can approximate, very closely, the shape of ideal dies for frictionless rod extrusion. Also, recent studies at Battelle(9) on the possibility of using curved dies for shell drawing have indicated that this form yields high-forming efficiency.

A measure of complexity of the extruded elliptic shape is the ratio of the major axis to the minor axis, A/B. When this ratio is equal to 1, the extruded product has a circular cross section. For A/B $\neq$ 1, extrusion with elliptic cross section is obtained. As the ratio A/B is progressively increased, the shape deviates more and more from a circle. A more general representation of the extruded shape complexity is the so-called "shape factor", S,(10) defined as:

$$\text{Shape Factor, } S = \frac{\text{Perimeter in Inches}}{\text{Weight in Pounds per Foot}} \ .$$

The shape factor, S, is a measure of the amount of surface that is generated per pound of metal extruded. This factor affects the production rate, and the cost of manufacture and maintenance of the dies. It is used by many extruders in Aluminum industry as a basis for pricing and gives the designer a means of comparing the relative complexity of alternate designs.

## Results of Numerical Calculations

Figure 2-2 shows the variation of extrusion pressure with the parameter A/B and with the shape factor, S, for a given set of process parameters ($m_d$, $C_1$, $C_3$) and reduction. As seen in this curve, the extrusion pressure increases rather slowly with the shape factor. The percentage increase in pressure, I, with increasing value of the shape factor is also given in

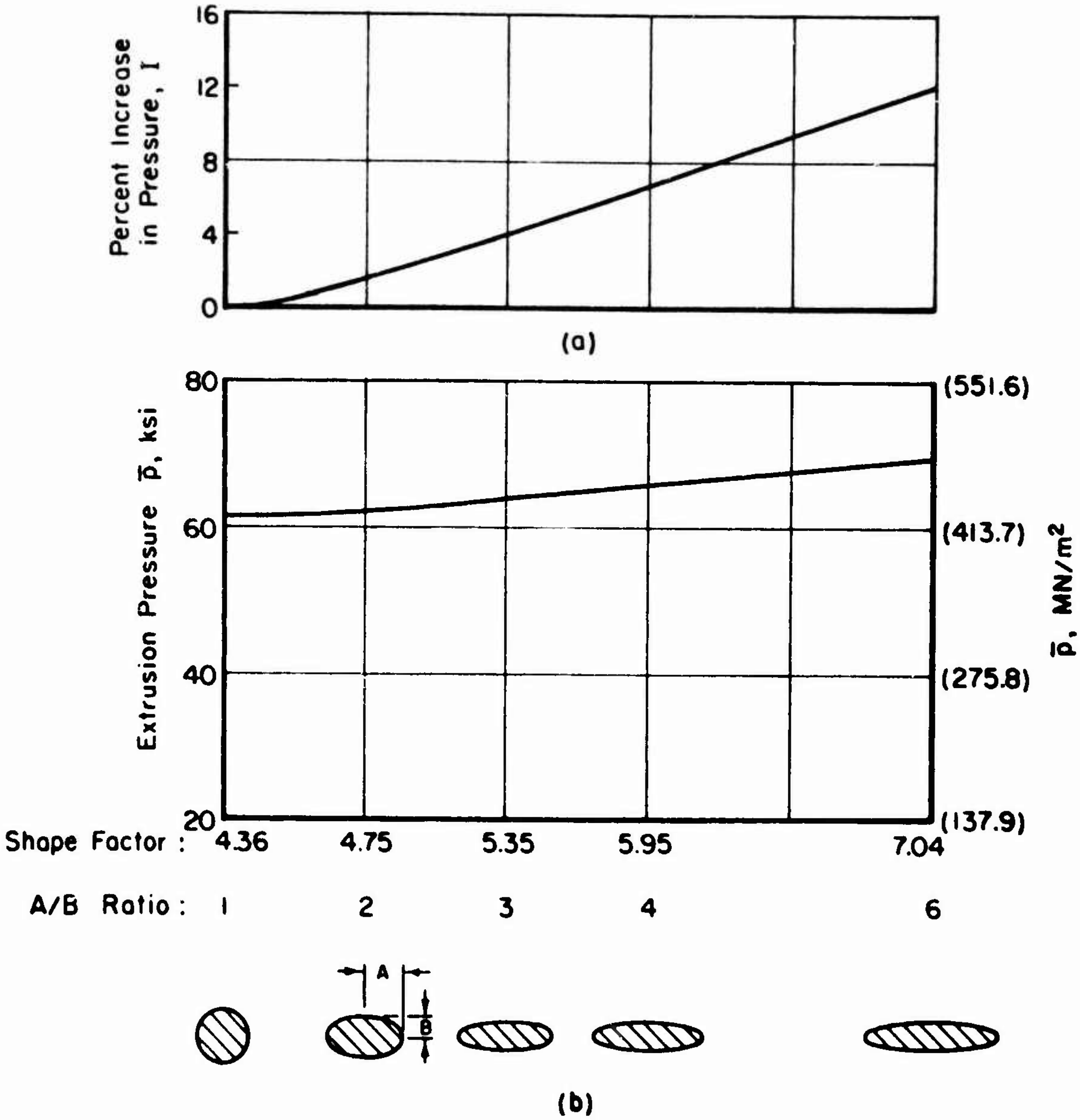



FIGURE 2-2. EXTRUSION PRESSURE AS A FUNCTION OF THE EXTRUDED SHAPE (Material = Al 1100, R = 1 inch, L = 1 inch, $m_d$ = 0.1, Reduction = 6.835, $C_1$ = $C_3$ = - 0.1)

Figure 2-2. An increase in pressure of only 12 percent is obtained when shape factor increases from 4.36 to 7.04. This slow rate of increase in mean pressure with shape change is not surprising. A similar observation has been made by Kast(11) in experimental investigation of the backward extrusion process by using punches with different shapes. Qualitatively, it is not difficult to explain this observation. The pressure variation increases with increasing shape factor, S, locally within the die cross section. However, the mean pressure is not influenced appreciably, provided the total reduction in area is kept constant.

Figure 2-3 shows the pressure variation with reduction in area for a given die, when the ratio A/B is kept equal to 2. As expected, the pressure increases with reduction in area. The extrusion pressure versus reduction in area for rod extrusion, A/B = 1, is also shown in Figure 2-3. The two curves follow each other very closely. The percentage increase in mean pressure due to shape change, I, decreases steeply with increasing reduction.

The determination of the optimum die profile is very important in lubricated extrusion. The criterion used to select the optimum die profile depends upon the end use of the extruded product. For rod extrusion, it is usually assumed that a die shape, which requires minimum rate of energy consumption, or pressure, also yields the minimum average strain in the extruded product. Thus, the optimum die shape is considered to be the shape which results in minimum extrusion pressure. The same criterion is used here for shape extrusion. It should be stated at this time that, due to the approximate nature of the upper-bound solution, the die profile obtained by minimizing the pressure will only approximate the optimum die configuration. Figure 2-4 shows the dependence of pressure upon the die shape parameters, namely, L, and $C_1$. For a given reduction, an optimum die length, L, and die profile coefficients, $C_1$ and $C_3$, can be determined such that the extrusion pressure is minimum. However, the variation of pressure near the optimum values of L, $C_1$, and $C_3$ is rather small. The saving in rate of energy consumption, by obtaining an optimum die, is not significant to justify the determination of the optimum die profile with great accuracy.

It is interesting to note that for the same reduction, the value of the optimum die length, $L_{opt} = 1.88$, obtained for elliptic extrusion, is very close to the optimum length, $L_{opt} = 2.0$, obtained for rod extrusion through a cosine-shape die.(12) Since the extrusion pressure varies only slightly near

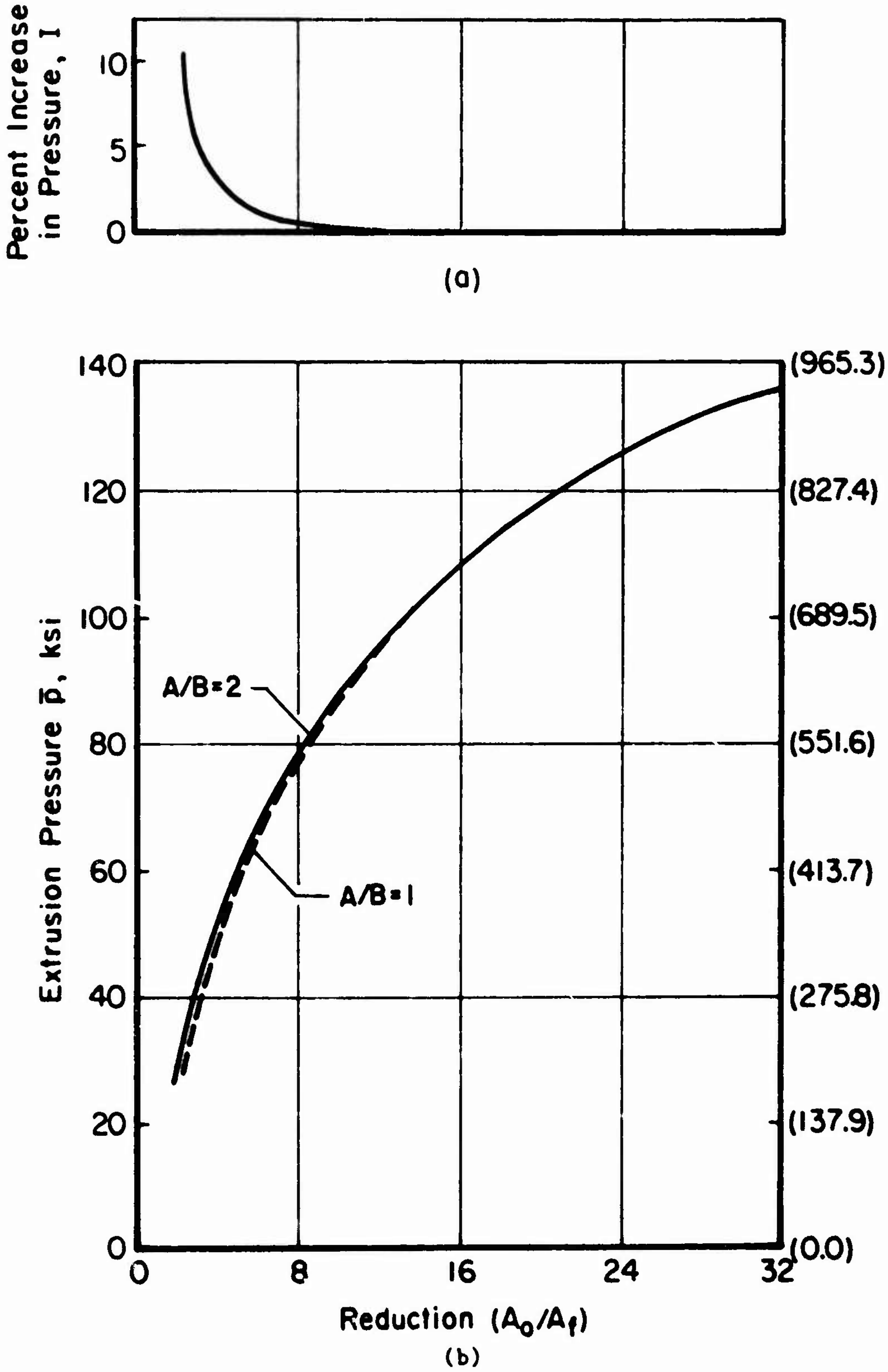



FIGURE 2-3. VARIATION OF EXTRUSION PRESSURE WITH REDUCTION

(Material = Al 1100, $m_d$ = 0.1, R = 1.0 inch, L = 0.65 inch, $C_1$ = $C_3$ = - 0.1)

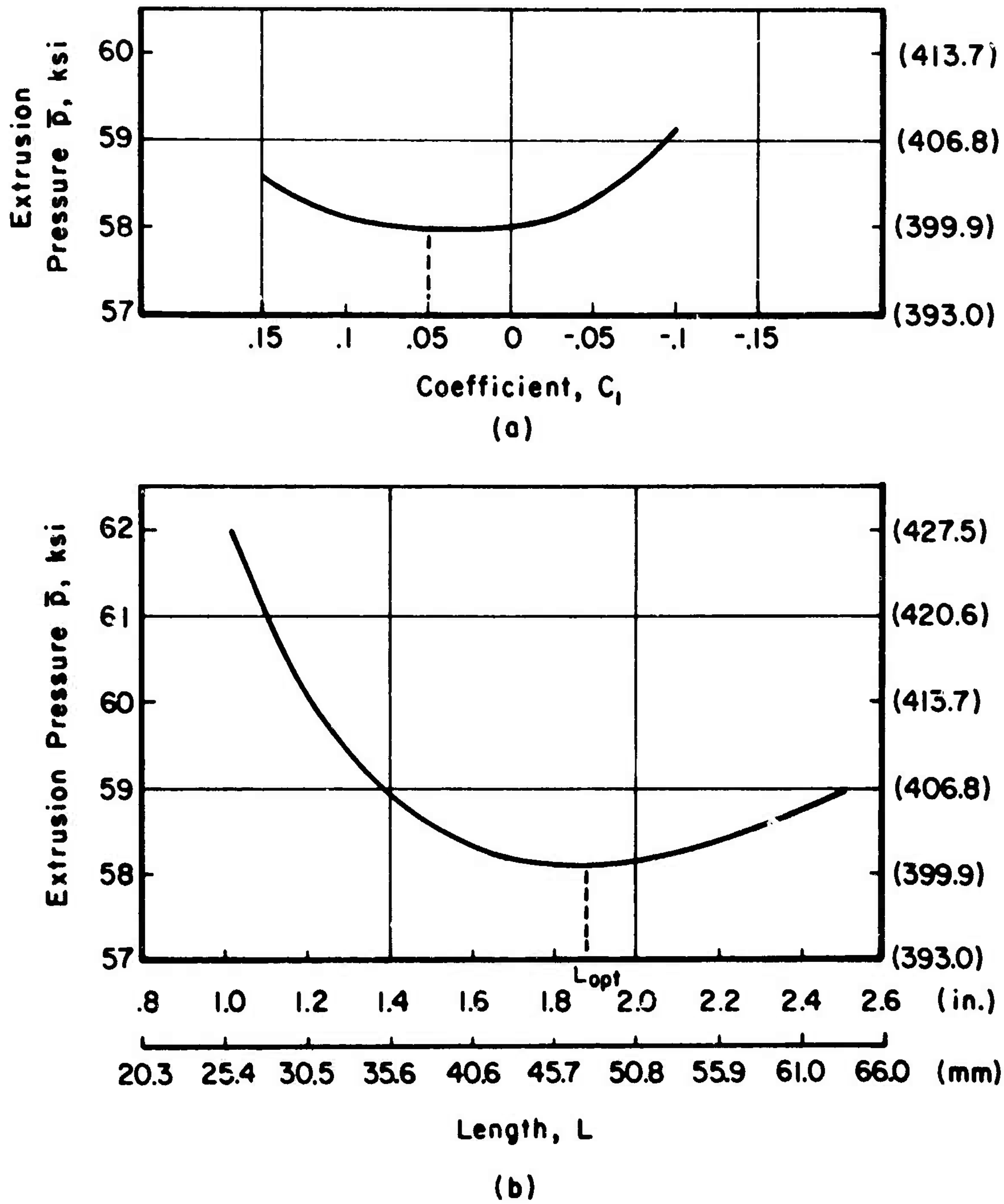



FIGURE 2-4. EXTRUSION PRESSURE AS A FUNCTION OF DIE GEOMETRY

(a) Pressure Versus Die Profile Coefficient, $C_1$ (L = 1.88 inch, $C_3$ = 0)

(b) Pressure Versus Die Length, L ($C_1$ = $C_3$ = 0)

(Material = Al 1100, $m_d$ = 0.1, R = 1 inch, Reduction = 6.835, A = 0.54 inch, B = 0.27 inch)

the optimum length, this suggests the possibility of selecting die length in shape extrusion by analyzing rod extrusion.

In a steady-state process, the streamlines also represent the paths followed by the material particles during deformation. In the present analysis, the metal flow along the die surface was determined from the velocity field. Paths followed by material points on the die surface are shown in Figure 2-5. Comparison of material path lines with experimental data[13] shows excellent agreement. As it is seen in Figure 2-5, the metal flow is not radial.

The following conclusions can be drawn from these numerical calculations:

(1) The mean pressure, necessary to extrude Al 1100 from a round stock to an elliptic shape, depends largely upon the reduction in area. The configuration of the extruded shape does not affect the extrusion pressure considerably, especially at high reductions.

(2) The use of dual stream functions, with appropriate numerical techniques, allows determination of an optimum smooth die configuration for lubricated extrusion from round to an elliptic shape. In this case, "optimum" is defined as the die shape which requires the minimum pressure for given material, friction factor, and extrusion ratio.

(3) Slight variations in the optimum die shape do not influence the extrusion pressure significantly.

(4) In extruding elliptic shapes, the velocity field, obtained by using dual stream functions, does not give a radial metal flow.

## Machining of the Die Surface

The die used for extruding elliptic-shaped modules has a complex three-dimensional surface. This surface cannot be easily machined by conventional methods like copy-turning or milling. Electrical-discharge machining (EDM) is one of the methods that can be used to manufacture such dies. In this process, the appropriate surface geometry is machined on an EDM electrode. This electrode is then used to EDM the rough-machined die

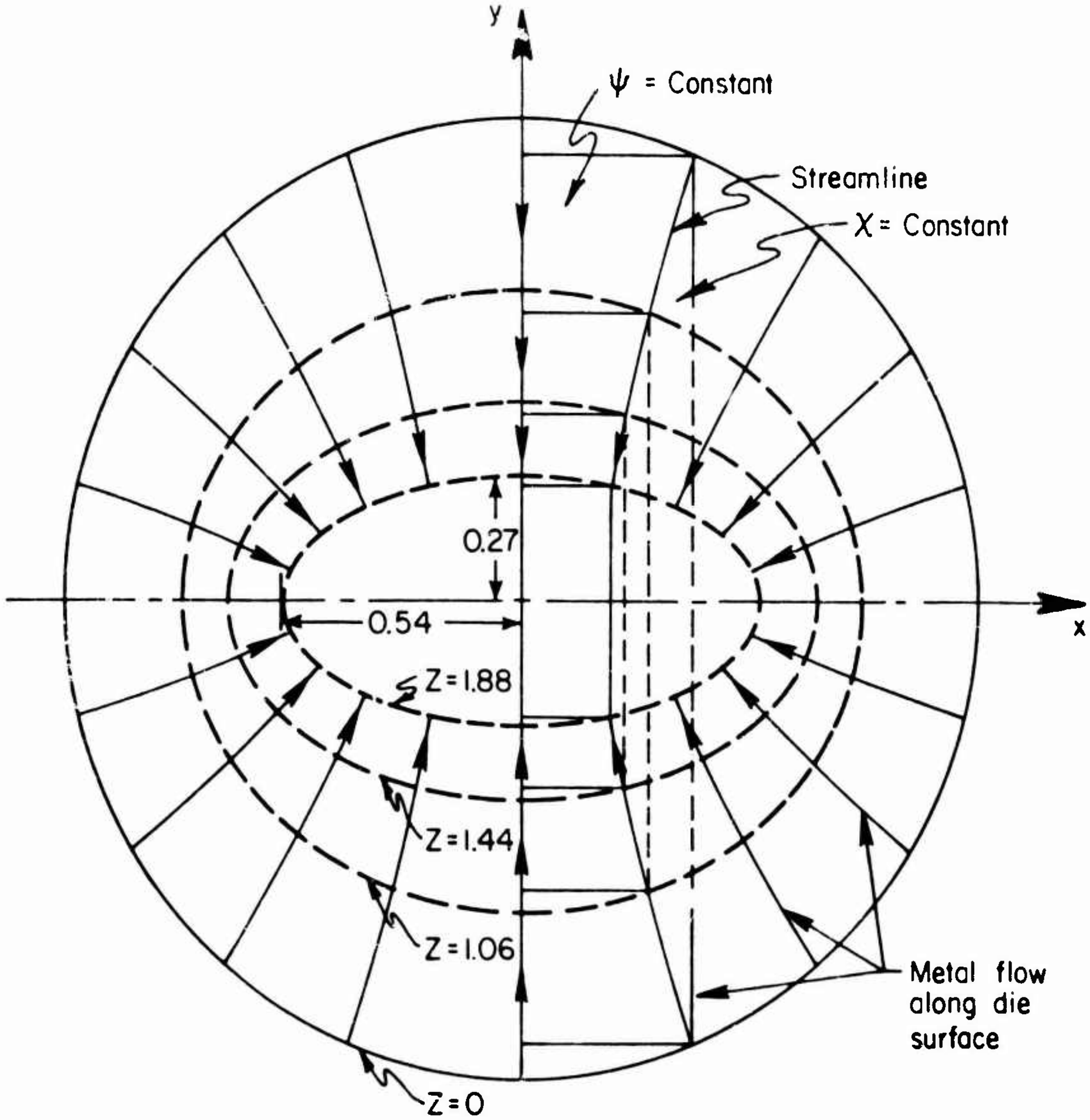



FIGURE 2-5. PATH FOLLOWED BY MATERIAL POINTS ALONG THE DIE SURFACE

block to generate the desired surface.

Standard APT (Automatically Programmed Tools) systems cannot be readily used to machine the EDM electrode needed for dies in our case. Therefore, special-purpose FORTRAN programs were developed for NC machining of the electrode. Appendix B gives the details of the mathematical derivations used in developing these computer programs. A wooden model of the EDM electrode was machined on an NC machine at Battelle, and it is seen in Figure 2-6. Visual and dimensional inspection of the machined surface indicated that the proper surface was generated.

## SUMMARY

This chapter describes the work conducted toward applying CAD/CAM techniques to a modular shape in shape-extrusion process. Most of the extruded shapes that find application in military hardware have relatively simple shapes like T, U, L, and Z. For these shapes, a rectangular module can be used as a building block for simulating the extrusion process.

In this study, the rectangular module has been approximated by an ellipse and the upper-bound method has been applied to analyze the mechanics of the process for extruding the modular shape. The analysis predicts the characteristics of metal flow, extrusion pressure, rate of energy required, and the effects of various process variables, such as reduction ratio, length of the die and material properties. Based on the analysis, computer programs were written to simulate the extrusion process.

The computer programs were used to analyze cold extrusion of Al 1100. A parametric study was made to determine the relation between shape change, reduction ratio, length and shape of the die, and the extrusion pressure. Comparison with existing data indicates that the proposed analysis and the computer programs adequately simulate the extrusion process.

The streamlined dies used for lubricated extrusion have a complex surface that provides a smooth transition from initial shape to the final shape. Such dies are made with the Electrical-Discharge Machining (EDM) process. For the selected modular shape, computer programs were written for NC machining of EDM electrode. Models made of wood were cut using the NC programs. Dimensional inspection of the models showed that the desired surface was generated accurately by NC machining.

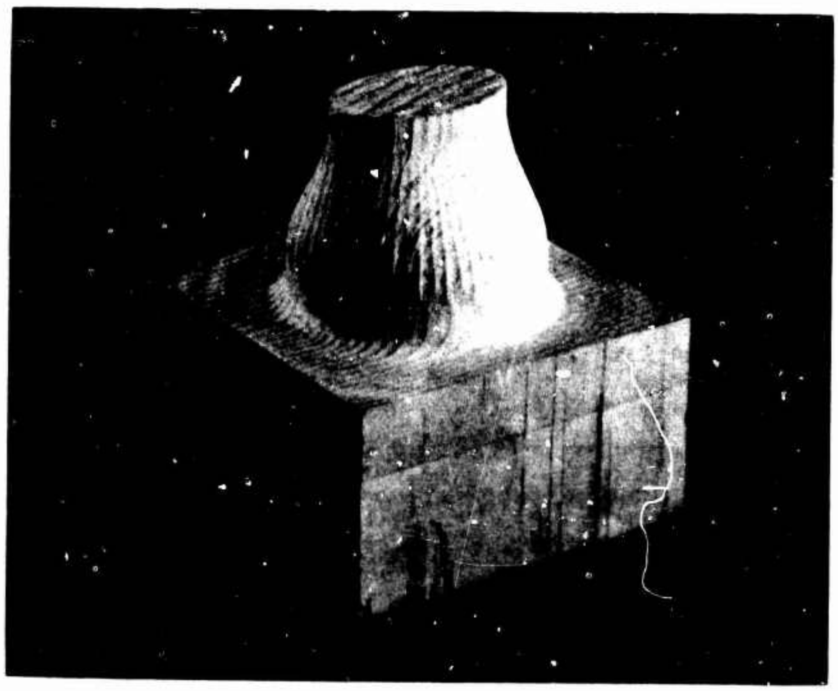


FIGURE 2-6. PHOTOGRAPH OF THE WOODEN MODEL OF THE EDM ELECTRODE FOR MANUFACTURING A STREAMLINED DIE TO EXTRUDE AN ELLIPTICAL CROSS SECTION FROM A ROUND BILLET

## REFERENCES


(1) Akeret, R., "Unconventional High-Speed Extrusion Processes for the Harder Aluminum Alloys", (in German), Z. Metallkunde, 64, 1973, pp 311-319.

(2) Lahoti, G. D., and Altan, T., "Prediction of Temperature Distributions in Tube Extrusion Using a Velocity Field Without Discontinuities", Proceedings of the Second North American Metalworking Research Conference, Madison, Wisconsin, May 20-22, 1974, pp 209-224.

(3) Seeds, W. E., "Preform Design for Gas Turbine Blades", Engineering Materials and Design, November, 1973, pp 27-31.

(4) Akgerman, N., Subramanian, T. L., and Altan, T., "Manufacturing Methods for a Computerized Forging Process for High-Strength Materials", Battelle's Columbus Laboratories, Technical Report AFML-TR-73-284, January, 1974.

(5) Nagpal, V., "General Kinematically Admissible Velocity Fields for Some Axisymmetric Metal-Forming Problems", Trans. ASME, J. Engineering for Industry, 96, 1974, p 1197.

(6) Nagpal, V., and Underwood, E. E., "Analysis of Axisymmetric Flow Through Curved Dies Using a Generalized Upper-Bound Approach", Proceedings of the Second North American Metalworking Research Conference, Madison, Wisconsin, May 20-22, 1974, pp 225-238.

(7) Yih, C. S., "Stream Functions in Three-Dimensional Flows", La Houille Blanche, 12, 1957, pp 445-450.

(8) Altan, T., and Boulger, F. W., "Flow Stress of Metals and Its Application in Metal-Forming Analysis", Trans. ASME, J. Engr. for Industry, 95, 1973, p 1009.

(9) Lahoti, G. D., and Altan, T., "Optimum Die Profile for Drawing of Shells and Cups", Proceedings of the Third North American Metalworking Research Conference, May, 1975, p 143.

(10) "Shape Design Manual", published by Alcan Aluminum Corporation, 111 West Fiftieth Street, New York, New York, 1964.

(11) Kast, D., "Model Laws in Backward Extrusion of Geometrically Similar Cups", (in German), Doctoral Dissertation, Technical University Stuttgart, 1969.

(12) Chen, P. C. T., and Ling, F. F., "Upper-Bound Solutions to Axisymmetric Extrusion Problems", Int. J. Mech. Sci., 10, pp 863-879, 1968.

(13) Yuen, David Pui-Kit, "The Flow Study of Shape Extrusions", Project Report submitted to Professor Shiro Kobayashi, Department of Mechanical Engrg., University of California, Berkeley, April, 1975.

# APPENDIX A

## ANALYSIS OF EXTRUSION OF AN ELLIPSE-SHAPED MODULE

## APPENDIX A

### ANALYSIS OF EXTRUSION OF AN ELLIPSE-SHAPED MODULE

This appendix gives the details of the theoretical analysis developed in this study, to determine:

(1) Load and energy required to extrude an ellipse-shaped module from a round billet

(2) Characteristics of metal flow such as velocity, strain, strain rate, and flow stress distribution during deformation

(3) Nonuniformity of strain across the cross section of the extruded elliptic shape

(4) Optimal die shape as function of process parameters such as shape of the extrusion, reduction in area, friction and material properties.

The analysis is based on the Upper-Bound Method. A kinematically admissible velocity field for the extrusion process is determined and used to form a solution which, in principle, gives an extrusion pressure larger than the actual pressure. The velocity field gives an approximate solution of the mechanics of metal flow.

### Analysis of Extrusion Process

A schematic representation of the extrusion of an ellipse-shaped part is seen in Figure 2-1. The symbols used are listed in the nomenclature at the end of this Appendix.

A billet of radius R is placed in the container of the extrusion press and pushed by the ram through a die. The die provides a smooth change in billet cross section and shape from a round to an ellipse of dimensions shown in Figure 2-1. In the analysis, the general case of extrusion of an off-centered elliptic shape is considered. Origin of the coordinate system is set at point O, which lies on the center of the round billet. Offsets C and D are measured along x and y axes, respectively. In the analysis, only steady-state extrusion is considered.

For the steady-state extrusion process, the portion of the material in the container (zone I, Figure 2-1) is nondeforming (rigid) and moves with a uniform velocity $V_o$. Plastic deformation of the material occurs in the die (zone II, Figure 2-1). The material leaving the die is again nondeforming and is assumed to have a uniform velocity. In the analysis, the following assumptions are made:

(a) The extruded material exits from the die with a uniform velocity parallel to the direction of the ram.

(b) Friction at material-container and material-die interfaces produces constant friction stresses at these interfaces.

(c) The cross sections of the die surface in x-y plane have elliptic boundaries.

## Die Profile

A general die surface which provides a smooth transition from circular to elliptic shape can be represented by

$$H(x,y,z) = \frac{[x-h(z)]^2}{g^2(z)} + \frac{[y-k(z)]^2}{f^2(z)} - 1 = 0 \quad , \tag{A-1}$$

$$\begin{aligned} \text{where} \quad & g(z) = f(z) = R && \text{at } z = 0 \\ & h(z) = k(z) = 0 && \text{at } z = 0 \quad , \\ \text{and} \quad & g(z) = A,\ f(z) = B && \text{at } z = L \\ & h(z) = C,\ k(z) = D && \text{at } z = L \quad . \end{aligned} \tag{A-2}$$

f, g, h, and k are some arbitrary functions of z and are restricted only by conditions (A-2). These functions are determined later to obtain optimal die configuration.

From Equation (A-1), at

$$z = 0, \; H = \frac{x^2}{R^2} + \frac{y^2}{R^2} - 1 = 0 \qquad \text{Equation of a circle of radius R}$$

and at

$$z = L, \; H = \frac{(x-C)^2}{A^2} + \frac{(y-D)^2}{B^2} - 1 = 0 \qquad \text{Equation of an ellipse with center } (x = C, \; y = D)$$

Thus, Equation (A-1) represents a smooth surface with a circle and an ellipse as its end boundaries.

Area Reduction

Initial cross-sectional area, $A_o$, of the billet is

$$A_o = \Pi R^2 \quad .$$

The final cross-sectional area, $A_f$, of the elliptic extrusion is given by

$$A_f = \Pi AB \quad .$$

Thus, percent area reduction, $R_A$, is

$$R_A = \frac{(A_o - A_f)}{A_o} \times 100$$

$$= \left(1 - \frac{AB}{R^2}\right) \times 100 \quad . \tag{A-3}$$

Kinematically Admissible Velocity Field

To form an upper-bound solution, a velocity field which satisfies all the kinematic conditions of the shape-extrusion process needs to be determined. The kinematic conditions that the chosen velocity field must satisfy are:

(a) Incompressibility condition, i.e.,

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} = 0 \quad . \tag{A-4}$$

(b) Velocity normal to die surface should be zero. A vector normal to a tool surface $H_t$ is grad($H_t$). Therefore,

$$(V_x\vec{i} + V_y\vec{j} + V_z\vec{k}) \cdot \mathrm{grad}(H_t) = 0 \quad ,$$

or $$V_x \frac{\partial H_t}{\partial x} + V_y \frac{\partial H_t}{\partial y} + V_z \frac{\partial H_t}{\partial z} = 0 \quad \text{at } H_t = 0 \ . \tag{A-5}$$

(c) Continuity condition, i.e., the component of velocity normal to the boundaries of the plastic zone must be continuous.

To simplify selection of an admissible velocity field, velocity fields for zones I, II and III of Figure 2-1 will be chosen separately and the shape of the plastic zone boundaries, which satisfy the condition of continuity between two zones, would be determined.

In zones I and III, the material is rigid and nondeforming and, therefore, the compressibility condition is automatically satisfied. Also, the material in these zones has uniform velocity perpendicular to the contacting tool surfaces, which fulfills the condition expressed by Equation (A-5). Thus, for zones I and III, admissible velocity fields are:

$$\begin{aligned} V &= V_o \qquad \text{for zone I} \\ V &= V_f \qquad \text{for zone III} \ . \end{aligned} \tag{A-6}$$

To select an admissible field for plastic zone II, concept of dual stream functions will be used.[7] According to this concept, velocity components in a 3-D incompressible flow can be represented in terms of two stream or flow functions $\psi$ and $\chi$, as follows:

$$V_x = \frac{\partial\psi}{\partial y}\frac{\partial\chi}{\partial z} - \frac{\partial\psi}{\partial z}\frac{\partial\chi}{\partial y}$$

$$V_y = \frac{\partial\psi}{\partial z}\frac{\partial\chi}{\partial x} - \frac{\partial\psi}{\partial x}\frac{\partial\chi}{\partial z}$$

$$V_z = \frac{\partial\psi}{\partial x}\frac{\partial\chi}{\partial y} - \frac{\partial\psi}{\partial y}\frac{\partial\chi}{\partial x} ,$$

or $$\vec{V} = V_x\vec{i} + V_y\vec{j} + V_z\vec{k} = (\text{grad}\,\psi) \times (\text{grad}\,\chi) . \qquad \text{(A-7)}$$

For zone II, the following expressions for stream functions are chosen to give admissible velocity field:

$$\psi = \frac{x-h(z)}{g(z)}$$

$$\chi = V_oR^2 \frac{(y-k(z))}{f(z)} . \qquad \text{(A-8)}$$

Substituting for $\psi$ and $\chi$ in Equation (A-7) yields:

$$V_x = V_oR^2\left(\frac{h'}{fg} + \frac{x-h}{fg^2}g'\right)$$

$$V_y = V_oR^2\left(\frac{k'}{fg} + \frac{y-k}{f^2g}f'\right)$$

$$V_z = V_oR^2 \frac{1}{fg} . \qquad \text{(A-9)}$$

From the expressions for strain-rate components derived later, it can be seen that incompressibility condition is satisfied. It can also be verified that

$$\text{grad}(H) \cdot (V_x\vec{i} + V_y\vec{j} + V_z\vec{k}) = 0 .$$

Thus, velocity normal to the die surface is zero. At vertical plane $z = 0$,

in zone II: $V_z = V_o$,

and in zone I: $V_z = V_o$ .

Thus, the velocity $V_z$ normal to surface z = 0 is continuous. Similarly, it can be shown that across the surface z = L, the normal velocity is continuous. Thus, the velocity field given by Equation (A-9) is kinematically admissible. This velocity field together with Equation (A-6) forms a complete admissible velocity field for the extrusion process, and can be used to formulate an upper-bound solution.

Strain-Rate Field

In zones I and III, all the components of the strain-rate tensor are zero. For zone II, the strain-rate components are given by:

$$\dot{\varepsilon}_{xx} = \frac{\partial V_x}{\partial x} = V_o R^2 \frac{g'}{fg^2}$$

$$\dot{\varepsilon}_{yy} = \frac{\partial V_y}{\partial y} = V_o R^2 \frac{f'}{f^2 g}$$

$$\dot{\varepsilon}_{zz} = \frac{\partial V_z}{\partial z} = - V_o R^2 \left( \frac{f'}{f^2 g} + \frac{g'}{g^2 f} \right)$$

$$\dot{\varepsilon}_{xy} = \frac{1}{2} \left( \frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial x} \right) = 0$$

$$\dot{\varepsilon}_{yz} = \frac{1}{2} \left( \frac{\partial V_y}{\partial z} + \frac{\partial V_z}{\partial y} \right)$$

$$= V_o \frac{R^2}{2} \left\{ \frac{k''}{fg} - \frac{2k'f'}{f^2 g} - \frac{k'g'}{fg^2} + y-k \left( \frac{f''}{f^2 g} - \frac{2f'^2}{f^3 g} - \frac{f'g'}{f^2 g^2} \right) \right\}$$

$$\dot{\varepsilon}_{xz} = \frac{1}{2} \left( \frac{\partial V_x}{\partial z} + \frac{\partial V_z}{\partial x} \right)$$

$$= V_o \frac{R^2}{2} \left\{ \frac{h''}{fg} - \frac{2h'g'}{fg^2} - \frac{h'f'}{f^2 g} + x-h \left( \frac{g''}{fg^2} - \frac{2g'^2}{fg^3} - \frac{g'f'}{f^2 g^2} \right) \right\}$$

**(A-10)**

Rate of Energy Dissipation and Extrusion Pressure

By the application of the Upper-Bound theorem,[6] expressions for the rate of energy dissipation, $\dot{E}$, and the mean pressure required to extrude, $\bar{P}$, which would give values that are larger than the actual values can be obtained. As sum of various components, the rate of energy dissipation, $\dot{E}$, is given by:

$$\dot{E} = \dot{E}_p + \dot{E}_1 + \dot{E}_2 + \dot{E}_{fd} + \dot{E}_{fc} + \dot{E}_{f\ell} \quad . \tag{A-11}$$

The rate of energy dissipation, $\dot{E}_p$, due to plastic deformation in zone II is given by:

$$\dot{E}_p = \frac{2}{\sqrt{3}} \iiint_{zyx} \bar{\sigma} \sqrt{\frac{1}{2} \dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij}} \; dx\, dy\, dz$$

$$= \frac{2}{\sqrt{3}} \iiint_{zyx} \bar{\sigma} \left[ 1/2 \left( \dot{\varepsilon}_{xx}{}^2 + \dot{\varepsilon}_{yy}{}^2 + \dot{\varepsilon}_{zz}{}^2 \right) + \dot{\varepsilon}_{yz}{}^2 + \dot{\varepsilon}_{zx}{}^2 \right]^{1/2} dx\, dy\, dz \tag{A-12}$$

The rate of energy loss due to tangential velocity discontinuity at the boundaries of plastic zone, or at material-tool interfaces, is given by:

$$\dot{E}_\Gamma = \int_\Gamma \tau |\Delta v| dS_\Gamma \quad . \tag{A-13}$$

$\tau$ is the shear stress at the surface $\Gamma$, $\Delta v$ is the tangential velocity discontinuity, and $S_\Gamma$ is the surface area.

The total rate of energy dissipation is equal to the rate of energy supplied by the ram, $\dot{E}_R$, which is given by:

$$\dot{E}_R = \Pi R^2 \bar{P} V_o \quad . \tag{A-14}$$

Substituting for various components of rate of energy dissipation in Equation (A-11), an expression for the mean extrusion pressure $\bar{P}$ can be obtained. In functional form, $\bar{P}$ may be written as:

$$\bar{P} = \bar{P}(A,B,C,D,R,V_o,L_c,L,L_a,g(z),f(z),h(z),k(z),m_d,m_c,\bar{\sigma}) \tag{A-15}$$

In the above expression, the friction at the material-tool interface is expressed by:

$$\tau = m\bar{\sigma} / \sqrt{3} \quad . \qquad \text{(A-16)}$$

$\tau$ is the shear stress due to friction at the tool surface; m is called the friction factor and is assumed to be constant over the tool surface for given conditions of lubrication, temperature, die and billet materials. $\bar{\sigma}$ is the flow stress of the material and it is assumed to be a function of the total strain ($\bar{\varepsilon}$), strain rate ($\dot{\bar{\varepsilon}}$) and temperature.

The pressure for given values of the parameters (A,B,C,D,R,$V_o$,g, f,h,k,L) was obtained numerically. The deformation zone, zone II in Figure 2-1, was divided into an orthogonal grid system. The grid was so chosen that it coincided with the stream surfaces ($\chi$ = Constant, $\psi$ = Constant). Thus, the volume elements of the grid could be considered as elements of the stream tubes. The total strain at the center of a volume element was obtained numerically by integrating along the center of the corresponding flow tube. Knowing the total strain, strain rate and temperature, the flow stress can be obtained from flow stress data.[8]

## Computer Program

Based on the foregoing analysis, a computer program, called EXTRUD, was developed to simulate the complete extrusion process. A listing of the computer program is included at the end of this Appendix. The following simplifications have been made in the computer program.

(1) Terms for friction at the container and die land are not included.

(2) The center of the elliptic shape coincides with the center of the billet. Thus, C and D are taken to be zero.

The program, however, can be easily generalized to include the effect of friction at container and die land, and the offset in the position of elliptic shape.

Input to the Computer Program

The following information is needed as input to the program:

| | | |
|---|---|---|
| DETAIL | = | .FALSE. when the detailed information regarding velocity and strain distribution is to be printed. |
| DEBUG | = | .FALSE. when the step-by-step calculations are to be printed for debugging the program. |
| OPTM | = | .TRUE. when the optimal shape of the die is to be determined. |
| R | = | Radius of the billet. |
| AL | = | Length of the die. |
| A,B,C,D | = | Dimensions of the ellipse (Figure 2-1). |
| AM | = | Friction shear factor ($m_d$). |
| TEMP | = | Initial temperature of the billet. |
| VO | = | Speed of the ram. |
| C1,C2,C3,C4, C5,C6,C7,C8 | = | Coefficients used in defining functions g(z), f(z), h(z), k(z) in polynomial form. In this program, only C1 and C3 are used. |
| NX,NZ | = | Number of divisions along the x and z axes, respectively, in which the deformation zone is divided for setting up a grid system. |
| NCODE | = | Specifies the shape of the billet. NCODE is equal to one for the cylindrical billet. |
| PG(4,3) | = | Arrays of size 4x3. Initial guesses of optimal C1, C3, and AL are input through this array. These guesses are used by the subroutine SIMPLX to determine the optimal values of C1, C3 and AL by the simplex method of function minimization. |

Output from the Computer Program

| | | |
|---|---|---|
| C1, C3, AL | = | For OPTM = .TRUE., optimal values of parameters C1, C3 and AL are printed. For OPTM = .FALSE., input values of C1, C3 and AL are printed. |
| ALOAD | = | Total load required to extrude. |
| PRES | = | Extrusion pressure |
| TENERG | = | Total rate of energy required for the extrusion process. |

## Nomenclature

| | | |
|---|---|---|
| $R$ | = | Radius of the billet. |
| $A$ | = | Half major axis of the elliptic shape. |
| $B$ | = | Half minor axis of the elliptic shape. |
| $C$ | = | Offset of the center of the elliptic shape along x axis. |
| $D$ | = | Offset of the center of the elliptic shape along y axis. |
| $L$ | = | Length of the streamlined die in axial direction (direction along the motion of the ram). |
| $V_o$ | = | Velocity of the ram. |
| $V_f$ | = | Velocity of the emerging product. |
| $Vx, Vy, Vz$ | = | Components of the velocity vector in x, y and z directions. |
| $\dot{\epsilon}_{ij}$ | = | Strain-rate tensor. |
| $\bar{\sigma}$ | = | Flow stress of the material. |
| $\dot{E}$ | = | Total rate of energy dissipation. |
| $\dot{E}_p$ | = | Rate of energy dissipation due to plastic deformation in zone II (Figure 2-1). |
| $\dot{E}_1, \dot{E}_2$ | = | Rate of energy dissipation due to tangential velocity discontinuity at boundaries z = 0 and z = L, respectively, of the plastic zone. |
| $\dot{E}_{fd}, \dot{E}_{fc}, \dot{E}_{f\ell}$ | = | Rate of energy dissipated due to friction at material die, material container, and material die-land interfaces, respectively. |
| $m_d, m_c$ | = | Friction shear factor over die and container surfaces, respectively. |
| $\bar{P}$ | = | Mean extrusion pressure. |

## COMPUTER PROGRAM LISTING

### COMPUTER PROGRAM FOR SIMULATION OF EXTRUSION OF AN ELLIPSE-SHAPED MODULE

```
      PROGRAM EXTRUD(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
      COMMON/LOG/DETAIL,DEBUG
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
      COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
     1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
      COMMON/COORD/GXL(11),GYL(11),GXR(11),GYR(11),XL(11,4)
     1          ,YL(11,4),XR(11,4),YR(11,4)
      COMMON/ENERG/EINT,ESHRL,ESHRR,EFRIC,TENERG,PRES,ALOAD
      COMMON/STRANT/EFSR(11,11),ET(11,11)
C
      DIMENSION PG(4,3),XX(3)
C***  NOMENCLATURE
C     R        RADIUS OF THE BILLET
C     AL       LENGTH OF THE DIE
C     A        HALF MAJOR AXIS OF ELLIPTIC EXTRUSION
C     B        HALF MINOR ASIS OF ELLIPTIC EXTRUSION
C     C        ECENTRICITY OF EXTRUSION ALONG X AXIS
C     D        ECENTRICITY OF EXTRUSION ALONG Y AXIS
C     AM       FRICTION FACTOR AT DIE-MATERIAL INTERFACE
C     TEMP     INITIAL TEMP OF BILLET
C     FSTRES   FLOW STRESS OF BILLET MATERIAL
C     NX       NUMBER OF DIVISIONS ALONG X-AXIS IN ONE QUADRANT
C     NZ       NUMBER OF AXIAL DIVISIONS
C     VO       VELOCITY OF THE BILLET
C     C1-C8    PARAMETERS DEFINING DIE SHAPE
      LOGICAL DETAIL,DEBUG,OPTM
      READ(5,99)DETAIL,DEBUG,OPTM
      IF(OPTM) GO TO 100
      READ(5,98)R,AL,A,B,C,D,AM,TEMP,VO
      READ(5,97)C1,C2,C3,C4,C5,C6,C7,C8
      READ(5,96) NX,NZ,NK,NCODE
      PRINT 95,R,AL,A,B,C,D,AM,TEMP,VO,NX,NZ,NK,NCODE
      CALL EGRATE
      PRINT 94,C1,C3,AL,ALOAD,PRES,TENERG
      GO TO 200
  100 READ(5,103)R,A,B,C,D,AM,TEMP,VO
      GO TO 300
  200 STOP
  300 CONTINUE
      DEBUG = .TRUE.
      READ(5,102)NX,NZ,NK,NSIMPL,NCODE
      PRINT 1001,R,A,B,C,D,AM,TEMP,VO,NX,NZ
      READ(5,800)(PG(I,1),I=1,4),(PG(I,2),I=1,4),(PG(I,3),I=1,4)
      PRINT 801, (PG(I,1),I=1,4),(PG(I,2),I=1,4),(PG(I,3),I=1,4)
```

```
C***  MINIMIZATION OF EXTRUSION PRESSURE BY SIMPLEX METHOD
      CALL SIMPLX(PG,3,4,0.5,0.5,2.5,XX,.001,40,NSIMPL)
      NX1=NX+1
      DETAIL =.FALSE.
      C1=XX(1)
      C3=XX(2)
      AL=XX(3)
      PRINT 1005
      CALL EGRATE
      PRINT 1003,C1,C3,AL,ALOAD,PRES,TENERG
   94 FORMAT(1H ,//20X,'OUTPUT FROM THE PROGRAM EXTRUD'///
     1       10X,'          VALUE OF DIE PARAMETER,C1 =',E15.6//
     2       10X,'          VALUE OF DIE PARAMETER,C3 =',E15.6//
     3       10X,'          VALUE OF DIE LENGTH,MM    =',E15.6//
     4       10X,'TOTAL FORCE REQD.  TO EXTRUDE,N     =',E15.6//
     5       10X,'PRESSURE REQUIRED TO EXTRUDE,MN/SQM=',E15.6//
     6       10X,'RATE OF ENERGY DISSIPATION,N.MM/SEC=',E15.6//)
   95 FORMAT(1H1,//20X,'INPUT DATA TO THE PROGRAM EXTRUD'///
     1       10X,'RADIUS OF THE BILLET,MM                =',F10.2//
     2       10X,'LENGTH OF THE DIE,MM                   =',F10.2//
     3       10X,'DIMENSIONS OF ELLIPTIC EXTRUSION           ',/
     4       10X,'HALF MAJOR AXIS,MM                     =',F10.2//
     5       10X,'HALF MINOR AXIS,MM                     =',F10.2//
     6       10X,'ECENTRICITY ALONG X AXIS,MM            =',F10.2//
     7       10X,'ECENTRICITY ALONG Y AXIS,MM            =',F10.2//
     8       10X,'                                           ',/
     9       10X,'FRICTION FACTOR AT INTERFACE           =',F10.2//
     1       10X,'INITIAL  TEMP.  OF THE BILLET,C        =',F10.2//
     2       10X,'VELOCITY OF THE BILLET,MM/SEC          =',F10.2//
     3       10X,'NUMBER OF DIVISIONS ALONG X-AXIS       =',I10//
     4       10X,'NUMBER OF AXIAL DIVISIONS              =',I10//
     5       10X,'INDEX FOR BILLET SHAPE                 =',I10//
     6       10X,'INDEX FOR DIE SHAPE                    =',I10/)
   96 FORMAT(4I10)
   97 FORMAT(8F8.4)
   98 FORMAT(9F8.4)
   99 FORMAT(3L4)
  102 FORMAT(5I10)
  103 FORMAT(8F8.4)
 1001 FORMAT(1H1,//20X,'INPUT DATA TO THE PROGRAM EXTRUD'///
     1       10X,'RADIUS OF THE BILLET,MM                =',F10.2//
     3       10X,'DIMENSIONS OF ELLIPTIC EXTRUSION           ',/
     4       10X,'HALF MAJOR AXIS,MM                     =',F10.2//
     5       10X,'HALF MINOR AXIS,MM                     =',F10.2//
     6       10X,'ECENTRICITY ALONG X AXIS,MM            =',F10.2//
     7       10X,'ECENTRICITY ALONG Y AXIS,MM            =',F10.2//
     8       10X,'                                           ',/
     9       10X,'FRICTION FACTOR AT INTERFACE           =',F10.2//
     1       10X,'INITIAL  TEMP.  OF THE BILLET,C        =',F10.2//
     2       10X,'VELOCITY OF THE BILLET,MM/SEC          =',F10.2//
     3       10X,'NUMBER OF DIVISIONS ALONG X-AXIS       =',I10//
     4       10X,'NUMBER OF AXIAL DIVISIONS              =',I10/)
```

```
 1003 FORMAT(1H ,//20X,'OUTPUT FROM THE PROGRAM EXTRUD'///
     1       10X,'OPTIMUM VALUE OF DIE PARAMETER,C1 =',E15.6//
     2       10X,'OPTIMUM VALUE OF DIE PARAMETER,C3 =',E15.6//
     3       10X,'OPTIMUM VALUE OF DIE LENGTH,MM    =',E15.6//
     4       10X,'TOTAL FORCE REQD. TO EXTRUDE,N    =',E15.6//
     5       10X,'PRESSURE REQUIRED TO EXTRUDE,MN/SQM=',E15.6//
     6       10X,'RATE OF ENERGY DISSIPATION,N.MM/SEC=',E15.6//)
 1005 FORMAT(1H ,//10X,'VELOCITY,STRAIN-RATE,AND STRAIN DISTRIBUTION'/
     1/2X,'  I    J    K                DISTANCE',10X,'VELOCITY',10X,
     2'STRAIN-RATE',3X,'STRAIN',5X,'FLOW STRESS',/,
     315X,'X',5X,'Y',5X,'Z',5X,'VX',5X,'VY',5X,'VZ',///)
  800 FORMAT(4F10.4)
  801 FORMAT(11X,'FOUR SETS OF INITIAL GUESSES FOR MINIMIZATION'//
     1       10X,'C1',5X,4(F10.4,5X)//10X,'C3',5X,4(F10.4,5X)//
     2       10X,'AL',5X,4(F10.4,5X)//)
        STOP
      END
      FUNCTION F(K,Z)
C THIS FUNCTION SUBPROGRAM EVALUATES THE FUNCTIONS
C G(Z), F(Z), H(Z),AND K(Z),WHICH DEFINE THE DIE SURFACE,
C AND THEIR FIRST AND SECOND DERIVATIVES.
C
C K IS A DUMMY INDEX WHICH DETERMINES THE PARTICULAR
C FUNCTION TO BE EVALUATED
C
      COMMON/LOG/DETAIL,DEBUG
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
C
      LOGICAL DETAIL,DEBUG
C     POLYNOMIAL DIE WITH ZERO ENTRANCE AND EXIT ANGLES
      GO TO (10,20,30,40,50,60,70,80,90,100,110,120),K
C
C     FUNCTION G(Z)
   10 F=R+ (C1*AL**2.0+2.0*C2*AL**3.0-3.0*(R-A)/AL**2.0)
     1  *Z**2.0 + (2.0*(R-A)/AL**3.0-2.0*C1*AL-3.0*C2*
     2  AL**2.0)*Z**3.0 +C1*Z**4.0 + C2*Z**5.0
      GO TO 130
C
C     FUNCTION F(Z)
   20 F=R+ (C3*AL**2.0+2.0*C4*AL**3.0-3.0*(R-B)/AL**2.0)
     1  *Z**2.0 + (2.0*(R-B)/AL**3.0-2.0*C3*AL-3.0*C4*
     2  AL**2.0)*Z**3.0 + C3*Z**4.0 + C4*Z**5.0
      GOTO 130
C
C     FUNCTION H(Z)
   30 F = (C5*AL**2.0+2.0*C6*AL**3.0+3.0*C/AL**2.0)
     1   *Z**2.0 + (-2.0*C/AL**3.0-2.0*C5*AL-3.0*C6
     2   *AL**2.0)*Z**3.0 + C5*Z**4.0 +C6*Z**5.0
      GO TO 130
C
C     FUNCTION K(Z)
   40 F = (C7*AL**2.0+2.0*C8*AL**3.0+3.0*D/AL**2.0)
     1   *Z**2.0 + (-2.0*D/AL**3.0-2.0*C7*AL-3.0*C8
```

```
     2    *AL**2.0)*Z**3.0 + C7*Z**4.0 + C8*Z**5.0
      GO TO 130
C
C     FUNCTION  G'(Z)  - FIRST DERIVATIVE OF G(Z)
   50 F = 2.0*(C1*AL**2.0+2.0*C2*AL**3.0-3.0*(R-A)/
     1    AL**2.0)*Z + 3.0*(2.0*(R-A)/AL**3.0-2.0*C1
     2     *AL-3.0*C2*AL**2.0)*Z**2.0 + 4.0*C1*Z**3.0
     3    + 5.0*C2*Z**4.0
      GO TO 130
C
C     FUNCTION  F'(Z) - FIRST DERIVATIVE OF F(Z)
   60 F = 2.0*(C3*AL**2.0+2.0*C4*AL**3.0-3.0*(R-B)/
     1    AL**2.0)*Z + 3.0*(2.0*(R-B)/AL**3.0-2.0*C3
     2     *AL-3.0*C4*AL**2.0)*Z**2.0 + 4.0*C3*Z**3.0
     3    + 5.0*C4*Z**4.0
      GO TO 130
C
C     FUNCTION H'(Z) - FIRST DERIVATIVE OF H(Z)
   70 F = 2.0*(C5*AL**2.0+2.0*C6*AL**3.0+3.0*C/AL**2.0)
     1    *Z + 3.0*(-2.0*C/AL**3.0-2.0*C5*AL-3.0*C6*AL**
     2    2.0)*Z**2.0 + 4.0*C5*Z**3.0 + 5.0*C6*Z**4.0
      GO TO 130
C
C     FUNCTION K'(Z) - FIRST DERIVATIVE OF K(Z)
   80 F= 2.0*(C7*AL**2.0+2.0*C8*AL**3.0+3.0*D/AL**2.0)
     1    *Z + 3.0*(-2.0*D/AL**3.0-2.0*C7*AL-3.0*C8*AL**
     2    2.0)*Z**2.0 + 4.0*C7*Z**3.0 + 5.0*C8*Z**4.0
      GO TO 130
C
C     FUNCTION G''(Z) - SECOND DERIVATIVE OF G(Z)
   90 F = 2.0*(C1*AL**2.0+2.0*C2*AL**3.0-3.0*(R-A)/AL
     1    **2.0) + 6.0*(2.0*(R-A)/AL**3.0-2.0*C1*AL-3.0
     2    *C2*AL**2.0)*Z + 12.0*C1*Z**2.0 + 20.0*C2*Z**3.0
      GO TO 130
C
C     FUNCTION F''(Z) - SECOND DERIVATIVE OF F(Z)
  100 F = 2.0*(C3*AL**2.0+2.0*C4*AL**3.0-3.0*(R-B)/AL
     1    **2.0) + 6.0*(2.0*(R-B)/AL**3.0-2.0*C3*AL-3.0
     2    *C4*AL**2.0)*Z + 12.0*C3*Z**2.0 + 20.0*C4*Z**3.0
      GO TO 130
C
C     FUNCTION H''(Z)  - SECOND DERIVATIVE OF H(Z)
  110 F = 2.0*(C5*AL**2.0+2.0*C6*AL**3.0+3.0*C/AL**2.0)
     1    +6.0*(-2.0*C/AL**3.0-2.0*C5*AL-3.0*C6*AL**2.0)
     2    *Z + 12.0*C5*Z**2.0 + 20.0*C6*Z**3.0
      GO TO 130
C
C     FUNCTION K''(Z)  - SECOND DERIVATIVE OF K(Z)
  120 F = 2.0*(C7*AL**2.0+2.0*C8*AL**3.0+3.0*D/AL**2.0)
     1    +6.0*(-2.0*D/AL**3.0-2.0*C7*AL-3.0*C8*AL**2.0)
     2    *Z + 12.0*C7*Z**2.0 + 20.0*C8*Z**3.0
      GO TO 130
C
  130 RETURN
```

```
      END
      SUBROUTINE FUNC(Z)
C
C THIS SUBROUTINE CALCULATES VARIOUS FUNCTIONS FOR
C GIVEN VALUE OF Z
C
      COMMON/LOG/DETAIL,DEBUG
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
      COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
     1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
C
      LOGICAL DETAIL,DEBUG
      FG=F(1,Z)
      FF=F(2,Z)
      FH=F(3,Z)
      FK=F(4,Z)
      FDG=F(5,Z)
      FDF=F(6,Z)
      FDH=F(7,Z)
      FDK=F(8,Z)
      F2G=F(9,Z)
      F2F=F(10,Z)
      F2H=F(11,Z)
      F2K=F(12,Z)
      SG=FG**2.0
      SF=FF**2.0
      F1=FF*SG
      F2=FG*SF
      SR=R**2.0
      F3=FF*FG
      IF(DEBUG) GO TO 63
      WRITE(6,104)
  104 FORMAT(1H ,55X,'FUNC(Z)')
      WRITE(6,105)Z,FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,F2F,F2H,F2K
  105 FORMAT(6F10.6,/,7F10.6)
   63 CONTINUE
      RETURN
      END
      FUNCTION EFFR(X,Y)
C
C THIS PROGRAM CALCULATES THE EFFECTIVE STRAIN RATE
C
      COMMON/LOG/DETAIL,DEBUG
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
      COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
     1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
C
      LOGICAL DETAIL,DEBUG
C     STRAIN RATE COMPONENTS
      EXX =(SR*FDG/F1)*VO
      EYY =(SR*FDF/F2)*VO
      EZZ = -(EXX+EYY)
```

```
      EXY = 0
      EYZ = 0.5*SR* (F2K/F3-2.*FDK*FDF/F2-FDK*FDG/F1+
     1     (Y-FK)*(F2F/F2-2.*FDF*FDF/(F2*FF)-FDF*FDG/(SG*SF)))*VO
      EXZ = 0.5*SR* (F2H/F3-2.*FDH*FDG/F1-FDH*FDF/F2+
     1     (X-FH)*(F2G/F1-2.*FDG*FDG/(F1*FG)-FDG*FDF/(SG*SF)))*VO
      EFFR=(2./SQRT(3.))*(.5*(EXX*EXX+EYY*EYY+EZZ*EZZ)
     1      +EXY*EXY+EYZ*EYZ+EXZ*EXZ)**.5
      IF(DEBUG) GO TO 20
      WRITE(6,10)
   10 FORMAT(1H ,55X,'EFFR(X,Y)')
      WRITE(6,15)X,Y,EXX,EYY,EZZ,EXY,EYZ,EXZ,EFFR
   15 FORMAT(9F8.3)
   20 CONTINUE
      RETURN
      END
      SUBROUTINE GRD(ZL,ZR)
C
C THIS SUBROUTINE GENERATES GRID POINTS IN THE PLANE
C SECTIONS AT Z=ZL AND Z=ZR
C
      COMMON/LOG/DETAIL,DEBUG
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
      COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
     1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
      COMMON/COORD/GXL(11),GYL(11),GXR(11),GYR(11),XL(11,4)
     1               ,YL(11,4),XR(11,4),YR(11,4)
C
      DIMENSION GX(11),GY(11)
      LOGICAL DETAIL,DEBUG
      NX1=NX+1
      ITER=1
      Z=ZL
      IF (ABS(Z).LT.1.0E-4)GO TO 30
C     PREVIOUS RIGHT SECTION IS NEW LEFT SECTION
      DO 10 I=1,NX1
      GXL(I)=GXR(I)
   10 GYL(I)=GYR(I)
   20 ITER=2
      Z=ZR
   30 AX=F(1,Z)
      AY=F(2,Z)
      ANX=NX
      GX(1)=0.0
      GY(NX1)=AY
        A1= 2.0*AX*(10./11.)/ANX
        AD=-(9./10.)*A1/(ANX-1.)
C
C CALCULATE THE COORDINATES OF GRID POINTS IN A SECTION
      DO 40 J=2,NX1
        IF(NK.NE.1) GO TO 32
        IF(J.EQ.2) GX(J)=A1
        IF(J.NE.2)GX(J)=GX(J-1)+(GX(J-1)-GX(J-2))+AD
        GO TO 35
```

```
 32       CONTINUE
        E1=J-1
        E1=E1/ANX
        GX(J)=E1*AX
 35       CONTINUE
C       SECTION IS ELLIPTIC
        IF(NK.EQ.1)GY(NX+2-J)=SQRT(ABS(1.0-(GX(J)/AX)**2))*AY
C        SECTION IS RECTANGULAR
        IF(NK.EQ.2)GY(NX+2-J)=(1.0-E1)*AY
C        SECTION IS TRIANGULAR
        IF(NK.EQ.3)GY(NX+2-J)=(1.0-E1)*AY
  40    CONTINUE
        IF(ITER.EQ.1) GO TO 80
C       HERE WHEN ZL IS NOT EQUAL TO ZERO
        DO 50 K=1,NX1
        GXR(K)=GX(K)
  50    GYR(K)=GY(K)
        GO TO 100
C       HERE WHEN Z=0
  80    CONTINUE
        DO 70 L =1,NX1
        GXL(L)=GX(L)
  70    GYL(L)=GY(L)
C       LEFT SECTION IS COMPLETED. GO TO COVER RIGHT SECTION
        GO TO 20
 100    CONTINUE
        IF(DEBUG) GO TO 53
        WRITE(6,101)
 101    FORMAT(1H ,25X,'GRD(ZL,ZR)',/)
        WRITE(6,102)ZL,ZR
 102    FORMAT(10X,'ZL=',F10.6,17X,'ZR=',F10.6)
        WRITE(6,103)(GXL(I),GYL(I),GXR(I),GYR(I),I=1,NX1)
 103    FORMAT(4F15.6)
  53    CONTINUE
        RETURN
        END
        SUBROUTINE STRAIN(ZL,ZR)
C
C THIS SUBROUTINE CALCULATES  GRID POINT COORDINATES,
C ELEMENTAL VOLUMES, AND STRAINS AND STRAIN-RATES
C AT CENTRE OF THE ELEMENTS
C
          COMMON/WRIT/ASURF,AVOLUM
        COMMON/LOG/DETAIL,DEBUG
        COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
        COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
        COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
       1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
        COMMON/COORD/GXL(11),GYL(11),GXR(11),GYR(11),XL(11,4)
       1             ,YL(11,4),XR(11,4),YR(11,4)
        COMMON/STRANT/EFSR(11,11),ET(11,11)
        COMMON/ENERG/EINT,ESHRL,ESHRR,EFRIC,TENERG,PRES,ALOAD
C
        LOGICAL DETAIL,DEBUG
```

```
      EINT=0.
C***  CALCULATE GRID POINT COORDINATES IN ALL FOUR
C     QUADRANTS W.R.T. TO THE COMMON ORIGIN
      CALL GRD(ZL,ZR)
      L=1
      Z=ZL
      CALL FUNC(Z)
      NX1=NX+1
      IF(ABS(Z).GE.1.E-4)GO TO 250
C***  HERE WHEN ZL=0
   10 DO 200 K=1,4
      GO TO (20,30,40,50),K
   20 FACX=1.0
      FACY=1.0
      GO TO 60
   30 FACX=-1.0
      FACY= 1.0
      GO TO 60
   40 FACX=-1.0
      FACY=-1.0
      GO TO 60
   50 FACX=1.0
      FACY=-1.0
   60 IF(L.EQ.2) GO TO 150
      DO 80 I=1,NX1
      X=FACX*GXL(I)+FH
      XL(I,K)=X
      Y=FACY*GYL(I)+FK
      YL(I,K)=Y
   80 CONTINUE
   90 CONTINUE
  200 CONTINUE
C
C     ZL = 0 AND LEFT SECTION IS COVERED. NOW COVER RIGHT SECTION
  100  L=2
      Z = ZR
      CALL FUNC(Z)
      GO TO 10
C***  HERE WHEN LEFT SECTION IS COVERED
  150 DO 170 I=1,NX1
      X=FACX*GXR(I)+FH
      XR(I,K)=X
      Y=FACY*GYR(I)+FK
      YR(I,K)=Y
  170 CONTINUE
      IF(K.EQ.4) GO TO 350
      GO TO 90
C     HERE WHEN ZL IS NOT ZERO
C***  PREVIOUS R.H. SECTION IS NEW L.H. SECTION
  250 DO 300 K=1,4
      DO 300 I=1,NX1
      XL(I,K) = XR(I,K)
  300 YL(I,K) = YR(I,K)
      L=2
```

```
      Z=ZR
      CALL FUNC(Z)
      GO TO 10
  350 CONTINUE
C
      IF(DEBUG) GO TO 365
      WRITE(6,380)
      WRITE(6,360)((K,I,XL(I,K),YL(I,K),XR(I,K),YR(I,K),I=1,NX1)
     1,K=1,4)
  360 FORMAT(2I10,4F15.6)
  365 CONTINUE
C***  CALCULATE VOLUMES OF ELEMENTS
C***  CALCULATE EFFECTIVE STRAIN-RATE AT CENTRE OF THE ELEMENT
C***  CALCULATE RATE OF ENERGY DISSIPATION DUE TO PLASTIC DEFORMATION
      Z = (ZL+ZR)/2.0
      CALL FUNC(Z)
      VZ =(SR/F3)*VO
      DO 400 K=1,4
      DO 400 I=1,NX
      IVAR=NX+1-I
      DLX=ABS(XL(I,K)-XL((I+1),K))
      DRX=ABS(XR(I,K)-XR((I+1),K))
      DO 400 J=1,IVAR
      IF(J.EQ.IVAR)FAC=0.5
      IF(J.NE.IVAR)FAC=1.0
      DZ=ABS(ZR-ZL)
      DLY=ABS(YL(J,K)-YL((J+1),K))
      DRY=ABS(YR(J,K)-YR((J+1),K))
      VOLUME     =(DLX*DLY + DRX*DRY +.5*(DLX*DRY+DLY*
     1            DRX))*DZ*FAC/3.
      IF(J.EQ.IVAR) GO TO 370
      X= (XL((I+1),K)+ XL(I,K)+ XR((I+1),K)+ XR(I,K))/4.
      Y= (YL((J+1),K)+ YL(J,K)+ YR((J+1),K)+YR(J,K))/4.
      GO TO 371
  370 X= (XL(I,K)+(1./3.)*(XL((I+1),K)-XL(I,K))+
     1    XR(I,K)+ (1./3.)*(XR((I+1),K)-XR(I,K)))/2.
      Y = (YL(J,K)+(1./3.)*(YL((J+1),K)-YL(J,K)) +
     1    YR(J,K) + (1./3.)*(YR((J+1),K)-YR(J,K)))/2.
  371 EFSR(I,J)=EFFR(X,Y)
       IF(K.NE.1)GO TO 374
      ET(I,J) = ET(I,J) + EFSR(I,J)*(ZR-ZL)/VZ
        AVOLUM=AVOLUM+ABS(VOLUME)
  374   CONTINUE
      FLOWS = FSTRES(ET(I,J),EFSR(I,J),TEMP)
      EINT = EINT+FLOWS*VOLUME*EFSR(I,J)
      IF(DETAIL) GO TO 373
      VX = SR*VO*(FDH/F3+(X-FH)*FDG/F1)
      VY = SR*VO*(FDK/F3+(Y-FK)*FDF/F2)
```

```
      VZ= SR*VO/F3
      WRITE(6,372)I,J,K,X,Y,Z,VX,VY,VZ,EFSR(I,J),ET(I,J),FLOWS
  372 FORMAT(2X,3I5,2X,4F11.3,/,5F11.3)
  373 CONTINUE
      IF(DEBUG) GO TO 390
      WRITE(6,380)
  380 FORMAT(1H ,55X,'STRAIN(ZL,ZR)',/)
      WRITE(6,385)X,Y,Z,VOLUME,EFSR(I,J),ET(I,J),FLOWS,EINT
  385 FORMAT(8F10.3)
  390 CONTINUE
  400 CONTINUE
      RETURN
      END
      FUNCTION   SURF(X1,Y1,Z1,X2,Y2,Z2,X3,Y3,Z3)
C
C     THIS SUBROUTINE CALCULATES THE AREA OF A TRIANGLE
      COMMON/LOG/DETAIL,DEBUG
      S12= SQRT((X1-X2)*(X1-X2) +(Y1-Y2)*(Y1-Y2) +(Z1-Z2)*(Z1-Z2))
      S23= SQRT((X2-X3)*(X2-X3)+(Y2-Y3)*(Y2-Y3) + (Z2-Z3)*(Z2-Z3))
      S31= SQRT((X3-X1)*(X3-X1) +(Y3-Y1)*(Y3-Y1) + (Z3-Z1)*(Z3-Z1))
      S =    (0.5*(S12+S23+S31))
      SURF= SQRT(S*(S-S12)*(S-S23)*(S-S31))
      RETURN
      END
      FUNCTION  DISVEL(X,Y,INDEX)
C
C THIS FUNCTION SUBPROGRAM DEFINES VELOCITY DISCONTINUITY
C AT THE DIE SURFACE, AT THE ENTRANCE BOUNDARY(Z=0) AND,
C AT THE EXIT BOUNDARY(Z=AL).
C
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
      COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
     1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
C
      VX = SR*VO*(FDH/F3+(X-FH)*FDG/F1)
      VY = SR*VO*(FDK/F3+(Y-FK)*FDF/F2)
      VZ= SR*VO/F3
      GO TO (10,10,20),INDEX
C     VELOCITY DISCONTINUITY AT ENTRANCE OR EXIT BOUNDARY
   10 DISVEL = SQRT(VX*VX+VY*VY)
      GO TO 30
C     VELOCITY DISCONTINUITY AT DIE SURFACE
   20 DISVEL = SQRT(VX*VX+VY*VY+VZ*VZ)
   30 RETURN
      END
      FUNCTION FSTRES(STRAIN,STRRAT,TEMP)
C***  THIS FUNCTION SUBPROGRAM CALCULATES FLOW STRESS
C     AS A FUNCTION OF STRAIN,STRAIN RATE AND TEMPERATURE
C
      FSTRES = 272.
      RETURN
      END
      SUBROUTINE ENERGY(ZL,ZR)
```

```
C***  THIS SUBROUTINE CALCULATES RATE OF ENERGY DISSIPATION
C     BETWEEN THE CONSECUTIVE SECTIONS  Z=ZL AND Z=ZR
C     NZ SHOULD BE MORE THAN ONE
C
        COMMON/WRIT/ASURF,AVOLUM
      COMMON/LOG/DETAIL,DEBUG
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,V0
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
      COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
     1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
      COMMON/STRANT/EFSR(11,11),ET(11,11)
      COMMON/COORD/GXL(11),GYL(11),GXR(11),GYR(11),XL(11,4)
     1             ,YL(11,4),XR(11,4),YR(11,4)
      COMMON/ENERG/EINT,ESHRL,ESHRR,EFRIC,TENERG,PRES,ALOAD
C
      LOGICAL DETAIL,DEBUG
      WRITE(6,21)
   21 FORMAT(1H ,55X,'ENERGY(ZL,ZR)',/)
      ESHRL=0.0
      ESHRR=0.0
      EFRIC=0.0
      CALL STRAIN(ZL,ZR)
C***  RATE OF ENERGY DISSIPATION
      DO 90 K=1,4
      DO 90 I=1,NX
      IVAR =NX+1-I
      DO 90 J=1,IVAR
      FLOWS=FSTRES(ET(I,J),EFSR(I,J),TEMP)
C**   SHEAR DEFORMATION ENERGY
      IF(ABS(ZL).GT.1.E-4)GO TO 60
C     HERE WHEN ZL = 0
      IF(J.EQ.IVAR) GO TO 40
      FAC=1.0
      FACCG=0.5
      GO TO 50
   40 FAC=0.5
      FACCG=(1.0/3.0)
      GO TO 50
   50 SAREA=FAC*(XL((I+1),K)-XL(I,K))*(YL((J+1),K)-YL(J,K))
      SAREA = ABS(SAREA)
      X = XL(I,K)+FACCG*(XL((I+1),K)-XL(I,K))
      Y = YL(J,K)+FACCG*(YL((J+1),K)-YL(J,K))
      IF(J.NE.1.OR.I.NE.1.OR.K.NE.1) GO TO 55
      CALL FUNC(ZL)
   55 CONTINUE
      DELV = ABS(DISVEL(X,Y,1))
      ESHRL=(FLOWS/SQRT(3.))*DELV*SAREA + ESHRL
   60 IF(ABS(ZR-AL).GT.1.E-4)GO TO 86
C     HERE WHEN ZR = AL
      IF(J.EQ.IVAR) GO TO 70
      FAC=1.0
      FACCG=0.5
      GO TO 80
   70 FAC=0.5
```

```
      FACCG=(1.0/3.0)
      GO TO 80
 80   SAREA=FAC*(XR((I+1),K)-XR(I,K))*(YR((J+1),K)-YR(J,K))
      SAREA = ABS(SAREA)
      X = XR(I,K)+FACCG*(XR((I+1),K)-XR(I,K))
      Y = YR(J,K)+FACCG*(YR((J+1),K)-YR(J,K))
      IF(J.NE.1.OR.I.NE.1.OR.K.NE.1) GO TO 85
      CALL FUNC(ZR)
 85   CONTINUE
      DELV =ABS(DISVEL(X,Y,2))
      ESHRR=(FLOWS/SQRT(3.))*DELV*SAREA + ESHRR
 86   CONTINUE
      IF(DEBUG) GO TO 89
      WRITE(6,87)FLOWS,SAREA,X,Y,DELV,ESHRL,ESHRR
 87   FORMAT(7F11.3)
 89   CONTINUE
 90   CONTINUE
C**   RATE OF ENERGY DISSIPATION DUE TO FRICTION
      DO 100 K=1,4
      DO 100 I=1,NX
      J=NX+2-I
      SURF1=SURF(XL(I,K),YL(J,K),ZL,XR(I,K),YR(J,K),
     1           ZR,XL((I+1),K),YL((J-1),K),ZL)
      SURF2= SURF(XR(I,K),YR(J,K),ZR,XL((I+1),K),YL((J-1),K),
     1           ZL,XR((I+1),K),YR((J-1),K),ZR)
        ASURF=ABS(SURF1+SURF2)+ASURF
      CALL FUNC(ZL)
      V1 = DISVEL(XL(I,K),YL(J,K),3)
      V2 = DISVEL(XL((I+1),K),YL((J-1),K),3)
      CALL FUNC(ZR)
      V3= DISVEL(XR(I,K),YR(J,K),3)
      V4 = DISVEL(XR((I+1),K),YR((J-1),K),3)
      AVEV = (V1+V2+V3+V4)/4.
      FLOWS1= FSTRES(ET(I,(J-1)),EFSR(I,(J-1)),TEMP)
      EFRIC = EFRIC+(1.0/SQRT(3.))*(FLOWS1*AVEV*(SURF1+SURF2))*AM
      IF(DEBUG) GO TO 93
      WRITE(6,92)ZR,ZL,SURF1,SURF2,V1,V2,V3,V4,FLOWS1,EFRIC
 92   FORMAT(5F12.4)
 93   CONTINUE
 100  CONTINUE
      IF(DEBUG) GO TO 73
      WRITE(6,113)EINT,ESHRL,ESHRR,EFRIC
 113  FORMAT(4F15.6)
 73   CONTINUE
      RETURN
      END
      SUBROUTINE EGRATE
        COMMON/WRIT/ASURF,AVOLUM
      COMMON/LOG/DETAIL,DEBUG
      COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,V0
      COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
      COMMON/MISC/FG,FF,FH,FK,FDG,FDF,FDH,FDK,F2G,
     1F2F,F2H,F2K,SG,SF,F1,F2,F3,SR
      COMMON/COORD/GXL(11),GYL(11),GXR(11),GYR(11),XL(11,4)
```

```
      1                ,YL(11,4),XR(11,4),YR(11,4)
       COMMON/STRANT/EFSR(11,11),ET(11,11)
       COMMON/ENERG/EINT,ESHRL,ESHRR,EFRIC,TENERG,PRES,ALOAD
       LOGICAL DETAIL,DEBUG
C***   DIVISION ALONG Z-AXIS IS IN ARITHMATIC PROGRESSION
C      SET INITIAL VALUES TO ZERO
       TEINT=0.0
       TESHRR=0.0
       TESHRL=0.0
       TEFRIC=0.0
         AVOLUM=0.
         ASURF=0.
       NX1=NX+1
       DO 15 K=1,4
       DO 15 I=1,NX1
       GXL(I)=0.
       GYL(I)=0.
       GXR(I)=0.
       GYR(I)=0.
       XL(I,K)=0.
       YL(I,K)=0.
       XR(I,K)=0.
       YR(I,K)=0.
       DO 15 J=1,NX1
       EFSR(I,J)=0.
       ET(I,J)=0.
   15  CONTINUE
       Z=0.0
       ILOOP=1
       ARA1 = 2.0*AL/(FLOAT(NZ)*(1.0+A*A/(R*R)))
       ARD=-(1.0-A*A/(R*R))*ARA1/(FLOAT(NZ)-1.)
       ZL=Z
       ZR=Z+ARA1
   10  CALL ENERGY(ZL,ZR)
       TEINT=TEINT+EINT
       TESHRL=TESHRL+ESHRL
       TESHRR=TESHRR+ESHRR
       TEFRIC=TEFRIC+EFRIC
       IF((ZR-AL).GT.-1.0E-4) GO TO 20
       IF(ILOOP.GT.22)GO TO 52
         ANEXT=(ZR-ZL)+ARD
       ZL=ZR
         ZR= ZR+ANEXT
       GO TO 10
   20  CONTINUE
       TENERG = TEINT + TESHRL + TESHRR + TEFRIC
       ALOAD = TENERG/VO
       PRES = TENERG/(3.1415927*SR*VO)
       WRITE(6,23)
   23  FORMAT(1H ,25X,'EGRATE',/)
       WRITE(6,24) TEINT,TESHRL,TESHRR,TEFRIC,TENERG,ALOAD,PRES
   24  FORMAT(7F11.3)
   33  CONTINUE
         WRITE(6,349)ASURF,AVOLUM
```

```
 249     FORMAT(2F15.6)
        RETURN
  52    STOP
        END
        FUNCTION MIN(XX,N)
        COMMON/PROP/R,AL,A,B,C,D,AM,TEMP,VO
        COMMON/DIES/C1,C2,C3,C4,C5,C6,C7,C8,NX,NZ,NK
        COMMON/ENERG/EINT,ESHRL,ESHRR,EFRIC,TENERG,PRES,ALOAD
        DIMENSION XX(N)
        C1=XX(1)
        C3=XX(2)
        AL=XX(3)
        CALL EGRATE
        MIN = PRES
        RETURN
        END
        SUBROUTINE SIMPLX(X,N,NP1,ALPA,BETA,GAMA,XX,ELIMIT,LIMIT,NPR)
C***    THIS SUBROUTINE MINIMIZES A FUNCTION OF N VARIABLES BY
C       SIMPLEX METHOD
C       DIMENSION STATEMENT IS TO BE CHANGED IF THE
C       NUMBER OF INDEPENDENT VARIABLES EXCEEDS 7
        DIMENSION X(NP1,N),Y(6),XAVG(6),X1(6),X2(6),XX(N),
       1EROR(6),XAV(6),DIF(6)
C
C       N IS THE NUMBER OF INDEPENDANT VARIABLES
C       (N+1) SETS OF INITIAL GUESSES OF INDEPENDANT VARIABLES MUST BE PRESCRIBED
C         IN THE ARRAY X(I,J), FOR I=1 TO (N+1), AND J=1, N
C       ALPA IS REFLECTION COEFFICIENT, A POSITIVE CONSTANT LESS THAN 1
C       BETA IS CONTRACTION COEFFICIENT, A POSITIVE CONSTANT LESS THAN 1
C       GAMA IS  XPANSION COEFFICIENT, A POSITIVE CONSTANT GREATER THAN 1
C
        ALPAP = 1. + ALPA
        BETAM = 1. - BETA
        GAMAM = 1. - GAMA
        FN = FLOAT(N)
        FNP1 = FN + 1.
        DO 13 J=1,N
  13    EROR(J)=1111.
        NITER = 0
        NPPP = 1
C
C
C*      CALCULATE Y(I) AT  INITIAL P(I)
        DO 20 I=1,NP1
        DO 15 J=1,N
  15    XX(J)=X(I,J)
        Y(I) = MIN(XX,N)
  20    CONTINUE
C
  30    CONTINUE
```

```
C*      PRINT ONLY WHEN REQUIRED
        NITER = NITER + 1
        IF(NPR.EQ.0)GO TO 40
        IF(NPPP.NE.NITER)GO TO 40
        NPPP = NPPP + 2
        WRITE(6,1001) NITER
 1001   FORMAT(20X,'NO. OF ITERATION =',I4,/,
       110X,' PRESSURE',5X,'ERROR IN C1',5X,'ERROR IN C3',
       25X,'ERROR IN AL',5X,'C1',10X,'C3',10X,'AL'/)
        DO 35   I=1,NP1
   35   WRITE(6,1000)I,Y(I),(EROR(J),J=1,N),(X(I,J),J=1,N)
 1000   FORMAT(5X,I4,7E10.3)
   40   CONTINUE
C       CALCULATE HIGH AND LOW VALUES OF Y (YH,HL) AND
C       THE POINTS AT WHICH THESE OCCUR (PH,PL).
        YH = Y(1)
        YL = Y(1)
        IH = 1
        IL = 1
        DO 101 I=2, NP1
        IF(Y(I).GT.YH)GO TO 50
        IF(Y(I).LT.YL)GO TO 60
        GO TO 101
   50   YH=Y(I)
        IH = I
        GO TO 101
   60   YL=Y(I)
        IL = I
  101   CONTINUE
C       CALCULATE CENTEROID OF POINTS(PBAR) WITHOUT INCLUDING
C       THE HIGH POINT(PH).
        DO 112 J=1, N
        XAVG(J) = 0.
        DO 104 I=1, NP1
        IF(I .EQ. IH) GO TO 104
        XAVG(J) = XAVG(J) + X(I,J)
  104   CONTINUE
  112   XAVG(J) = XAVG(J)/FN
        DO 113 J=1, N
  113   X1(J) = ALPAP*XAVG(J) - ALPA*X(IH,J)
C       CALCULATE Y AT REFLECTION OF HIGH POINT(Y*)
        Y1 = MIN(X1,N)
        IF(Y1 .LT. YL) GO TO 200
C       HERE IF Y* IS  LESS THAN YL
  250   CONTINUE
        DO 109 I=1, NP1
        IF(I .EQ. IH) GO TO 109
        IF(Y1 .GT. Y(I)) GO TO 600
  109   CONTINUE
        GO TO 700
  600   CONTINUE
C       Y* IS GREATER THAN Y(I) WITH I NOT EQUAL TO H
        IF(Y1 .GT. YH) GO TO 850
C       HERE WHEN Y* IS LESS THAN YH
```

```
  750 CONTINUE
      DO 115 J=1, N
C     REPLACE PH BY P*
  115 X(IH,J) = X1(J)
      Y(IH) = Y1
  850 CONTINUE
C     FORM P** BY CONTRACTION
      DO 116 J=1, N
  116 X2(J) = BETA*X(IH,J) + BETAM*XAVG(J)
      Y2 = MIN(X2,N)
      IF(Y2 .GE. YH) GO TO 800
  950 CONTINUE
C     HERE WHEN Y** IS LESS THAN YH .
C     REPLACE PH BY P**
      DO 117 J=1, N
  117 X(IH,J) = X2(J)
      Y(IH) = Y2
      GO TO 400
C     HERE WHEN Y** IS GREATER THAN YH
  800 CONTINUE
C     REPLACE ALL P(I)'S BY (P(I)+PL)/2
      DO 105 I=1, NP1
      DO 99 J=1, N
      X(I,J) = (X(I,J) + X(IL,J))/2.
   99 XX(J) = X(I,J)
      Y(I) = MIN(XX,N)
  105 CONTINUE
      GO TO 400
  200 CONTINUE
C     HERE IF Y* IS LESS THAN YL
C     EXPAND P* TO P** AND CALCULATE Y**
      DO 118 J=1, N
  118 X2(J) = GAMA*X1(J) + GAMAM*XAVG(J)
      Y2 = MIN(X2,N)
      IF(Y2 .LT. YL) GO TO 300
      GO TO 700
C     HERE WHEN Y** IS LESS THAN YL
C     REPLACE PH BY P**
  300 CONTINUE
      DO 119 J=1, N
  119 X(IH,J) = X2(J)
      Y(IH) = Y2
      GO TO 400
  700 CONTINUE
C     HERE WHEN Y** IS GREATER THAN YL
C     REPLACE PH BY P*
      DO 121 J=1, N
  121 X(IH,J) = X1(J)
      Y(IH) = Y1
  400 CONTINUE
```

```
C       CHECK FOR MINIMUM
        DO 401 J=1,N
  401   XAV(J)=0.
        DO 305 I=1, NP1
        DO 305 J= 1,N
  305   XAV(J)=XAV(J)+X(I,J)
        DO 402 J=1,N
        XAV(J)= XAV(J)/FNP1
  402   EROR(J)=0.
        DO 301 I=1, NP1
        DO 403 J=1,N
        DIF(J)= X(I,J)-XAV(J)
  403   EROR(J)=EROR(J)+DIF(J)*DIF(J)
  301   CONTINUE
        DO 404 J=1,N
  404   EROR(J)= SQRT(EROR(J)/FNP1)
        DO 777 I=1, NP1
        DO 777 J=1, N
   777  IF(X(I,J) .LT. 0.) X(I,J)=0.
        IF(NITER .GE. LIMIT) GO TO 554
        DO 405 J=1,N
  405   IF(EROR(J).GT.ELIMIT) GO TO 30
        GO TO 555
C
  554   WRITE(6,553)
  553   FORMAT(10X,'MIN. NOT DETERMINED IN THE SPECIFIED ITERATIONS'/)
        GO TO 555
   555  CONTINUE
        DO 122 J=1, N
        XX(J) = 0.
        DO 123 I=1, NP1
   123  XX(J) = XX(J) + X(I,J)
   122  XX(J) = XX(J)/FNP1
        RETURN
        END
```

# APPENDIX B

## NUMERICAL CONTROL (NC) MACHINING OF EDM ELECTRODE

APPENDIX B

## NUMERICAL CONTROL (NC) MACHINING OF EDM ELECTRODE

This Appendix includes the mathematical derivations used in developing the computer program for NC machining of the EDM Electrode. A listing of the computer program is included at the end of this Appendix.

In NC machining, the rotating cutter is moved along some specified path to generate the desired surface. To move the cutter along this path, the information on the coordinates of the center of the cutter is fed to the NC machine via a punched tape. For the present case, APT (Automatically Programmed Tools) routines are not adequate to give the positions of the cutter. Thus, special-purpose FORTRAN program DIECUT was written to generate the NC tape.

### Mathematical Basis

The surface to be generated is described by the Equation

$$H(x,y,z) = \frac{[x-h(z)]^2}{g^2(z)} + \frac{[y-k(z)]^2}{f^2(z)} - 1 = 0 \; , \qquad \text{(B-1)}$$

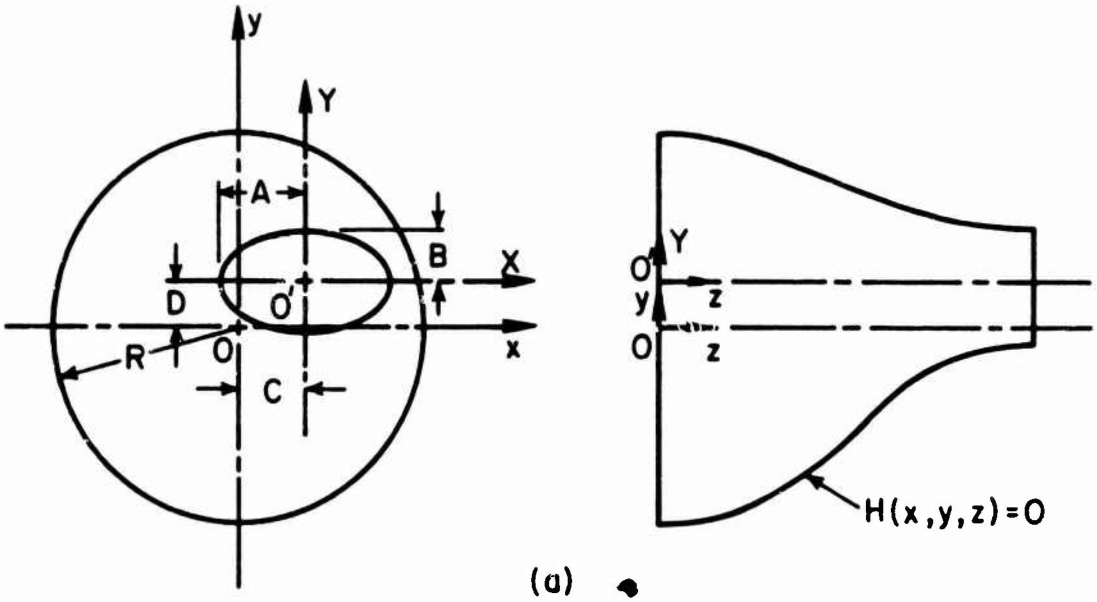
where g(z), f(z), h(z) and k(z) are functions defining die surface, as explained in Appendix A. Point 0 is the origin of the (x,y,z) cartesian coordinate system, as seen in Figure B-1. To traverse the surface, a ball-end mill is moved along radial planes perpendicular to x-y plane and passing through the point 0'. The Equation of the electrode surface with respect to new coordinate system (X,Y,z) with origin at point 0' is

$$H_d = \frac{(X + C - h)^2}{g} + \frac{(Y + D - k)^2}{f} - 1 = 0 \; . \qquad \text{(B-2)}$$

### Cutter Paths

The electrode surface is cut along the radial paths shown in Figure B-1. The Equation of any such radial plane is

$$\tan\theta = Y/X \; , \qquad \text{(B-3)}$$



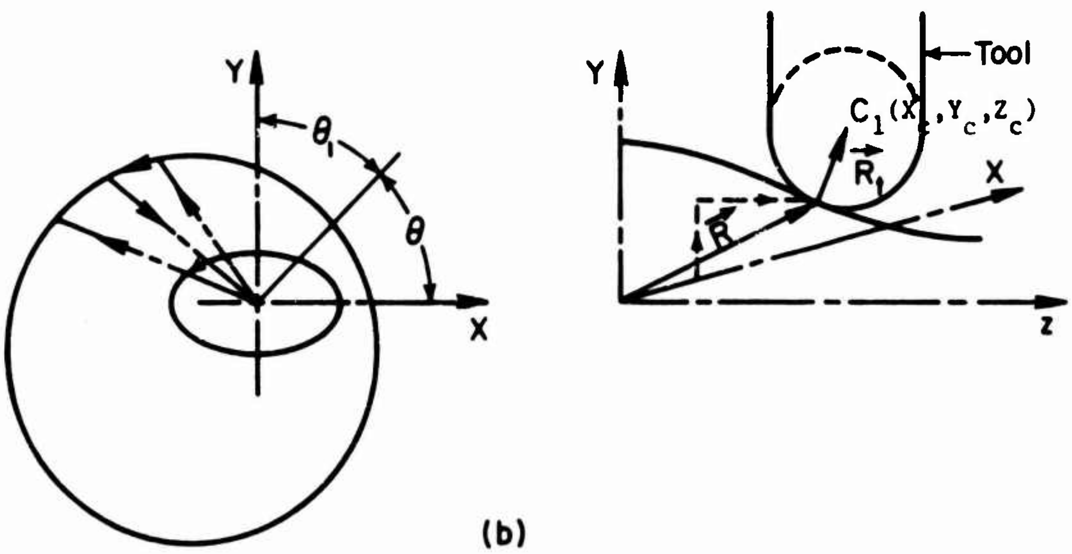




FIGURE B-1. NC MACHINING OF THE ELECTRODE TO EDM THE EXTRUSION DIE

(a) Surface of the EDM electrode

(b) Cutter path along radial planes and position of the cutter center $C_1$

where $\theta$ is the angle measured from X axis. This plane intersects the surface $H_d$ in two curves. The Equations of these curves are obtained by substituting Equation (B-3) in Equation (B-2) which yields

$$X = -\frac{b \pm \sqrt{b^2 - 4a\,c}}{2a} \quad , \; Y = X \tan\theta \quad , \tag{B-4}$$

where
$$a = f^2 + g^2 \tan^2\theta$$
$$b = 2f^2C + 2 \tan\theta\, g^2D - 2f^2h - 2 \tan\theta\, kg^2$$
$$c = f^2C^2 + f^2h^2 - 2f^2hC + g^2D^2 + g^2k^2 - 2g^2kD - f^2g^2 \; . \tag{B-5}$$

<u>Position of Cutter Center</u>

In order to determine the coordinates of the center of the ball-end mill, the position of the cutter center $C_1$, with respect to the curved path line given by Equation (B-4), is determined. A vector normal to the surface $H_d$ is

$$\text{grad}(H_d) = A_x\vec{i} + A_y\vec{j} + A_z\vec{k} \quad , \tag{B-6}$$

where
$$A_x = \frac{X + C - h}{g^2} \quad , \quad A_y = \frac{Y + D - k}{f^2} \quad ,$$

$$A_z = \frac{(X + C - h)^2}{g^3} g' + \frac{(X + C - h)}{g^2} h' + \frac{(Y + D - k)}{f^3} f' + \frac{(Y + D - k)}{f^2} k'$$

Let $R_t$ be the radius of the spherical tool. Then the vector $\vec{R}_t$ of magnitude equal to $R_t$ and normal to surface $H_d$ is

$$R_t = R_x\vec{i} + R_y\vec{j} + R_z\vec{k} \quad , \tag{B-7}$$

where
$$R_x = R_t \cdot \frac{A_x}{[A_x{}^2 + A_y{}^2 + A_z{}^2]^{1/2}}$$

$$R_y = R_t \cdot \frac{A_y}{[A_x{}^2 + A_y{}^2 + A_z{}^2]^{1/2}}$$

$$R_z = R_t \cdot \frac{A_z}{[A_x{}^2 + A_y{}^2 + A_z{}^2]^{1/2}} \; .$$

As shown in Figure B-1, the coordinates ($X_c$, $Y_c$, $Z_c$) of the cutter center are then given by

$$X_c = X + R_x \tag{B-8}$$

$$Y_c = Y + R_y$$

$$Z_c = z + R_z \quad ,$$

where $R_x$, $R_y$, $R_z$ are determined at point (X, Y, z).

## Computer Program

Based on the foregoing derivations, a computer program called DIECUT was developed to determine, numerically, the cutter positions. DIECUT was coded and debugged on a PDP-11 computer. Routines PNCHNC and STORE, which is written in Assembly Language, are used with DIECUT to generate NC tape in EIA code. A listing of the programs is attached.

### Input to the Program DIECUT

The following information is needed as input to the program DIECUT:

R = Radius of the billet.

AL = Length of the die.

A,B,C,D = Dimensions of the ellipse (Figure B-1).

NDELZ = (NDELZ + 1) is the number of points at which the cutter position is determined along a radial path line.

DELT = Number of divisions in which the surface $H_d$ is divided radially.

IQUAD = Number of quadrants for which NC tape is to be generated. IQUAD can be equal to one, two, or four.

In DIECUT, subprogram function F(K,Z) gives the expressions for functions f(z), g(z), h(z) and k(z). The given listing shows the expressions for these functions when a cosine form is assumed for them. When other forms like polynomial or straight-lines are chosen for functions f, g, h and k, subprogram function F(K,Z) should be accordingly modified.

Output from the Program DIECUT

A paper tape is obtained as output from the program. The tape has coordinates of the cutter path punched on it in EIA code. This tape is used to machine the EDM electrode.

# COMPUTER PROGRAM LISTING

## COMPUTER PROGRAM FOR NC MACHINING OF EDM ELECTRODE

```
C PROGRAM DIEECUT
C DETERMINES CUTTER PATHS FOR N/C MACHINING
C OF A DIE FOR EXTRUDING ROUND TO OFF-CENTRE
C ELLIPTIC SHAPE

C CODED BY DR. ? NAGPAL,
C PROGRAM COMPILED AND DEBUGGED ON PDP 11
C
C   A= RADIUS OF THE CYLINDRICAL BILLET
C   AL=LENGTH OF THE DIE
C      DIMENSIONS OF THE ELLIPTIC EXTRUSION
C   2A=MAJOR AXIS
C   2B=MINOR AXIS
C      ECENTRICITY OF EXTRUSION
C   C= ECENTRICITY ALONG X AXIS
C   D= ECENTRICITY ALONG Y AXIS
C   RT=RADIUS OF SPHERICAL BALL MILLING TOOL

      COMMON/DIEPAR/R,AL,A,B,C,D,NDELT,NDELZ
      COMMON/THETAP/THETA,T1,T2
      COMMON/COORD/XC1,YC1,XC2,YC2
      COMMON/CUTTER/RT,RX1,RY1,RZ1,RX2,RY2,RZ2

      DIMENSION X2(25),Y2(25),Z2(25),X1(25),Y1(25),Z1(25)
C      IQUAD CAN ONLY BE ONE,TWO,OR FOUR

      READ(5,10)R,AL,A,B,C,D,RT
C NDELT SHOULD BE DIVISIBLE BY FOUR
      READ(5,15)NDELT,NDELZ,IQUAD
 15   FORMAT(I4)
  10  FORMAT(F14.7)
C
C     SET UP A FILE  TO  STORE COORDINATES OF POINTS FOR
C     THETA BETWEEN 180 AND 360 DEGREES
      NT1=NDELT+1
      IS=6*(NDELZ+1)
      DEFINE FILE 2 (NT1,IS,U,IVAR)
      IVAR=1
D      WRITE(5,20)R,AL,A,B,C,D,RT,NDELT,NDELZ
D   20 FORMAT(1H1,///20X,'INPUT DATA TO THE PROGRAM DIECUT'///
D    1       10X,'RADIUS OF CYLINDRICAL BILLET,MM    =',F15.6//
D    2       10X,'LENGTH OF THE DIE,MM               =',F15.6//
D    3       10X,'DIMENSIONS OF EXTRUSION, A,MM      =',F15.6//
```

```
D     4        10X,'                                    B,MM      =',F15.6//
D     5        10X,'                                    C,MM      =',F15.6//
D     6        10X,'                                    D,MM      =',F15.6//
D     7        10X,'RADIUS OF SPHERICAL CUTTER,RT,MM =',F15.6//
D     8        10X,'NUMBER OF RADIAL DIVISIONS,       =',I10//
D     9        10X,'NUMBER OF LONGITUDINAL DIVISIONS,=',I10/)
            IC=2
            THETA=0.0
            Z=AL
            T1=3.1415927*80.0/180.0
            T2=3.1415927*100./180.0
            NZ1=NDELZ+1
            ANZ =NDELZ
            DELZ=AL/ANZ
            ANT =NDELT
            DELT=3.1415927*2.0/ANT
             GO TO (21,22,24,23),IQUAD
       21    NDELT2=NDELT/4+1
             GO TO 24
       22    NDELT2=NDELT/2+1
             GO TO 24
       23    NDELT2=NDELT/2
             GO TO 24
       24    CONTINUE
D            CALL LEADER
C
C            MOVE TO INITIAL POSITION
             X1(1)=0.0
             Y1(1)=0.0
             Z1(1)=-1.0
             WRITE(5,217)X1(1),Y1(1),Z1(1)
             CALL PNCHNC (X1,Y1,Z1,-1)
             X1(1)=A+ RT + C
             Y1(1)=0.0
             Z1(1)=-1.
             WRITE(5,217)X1(1),Y1(1),Z1(1)
D            CALL PNCHNC(X1,Y1,Z1,1)

       40   DO 200 I=1,NDELT2
       50   DO 150 J=1,NZ1
            IF(THETA.GE.T1.AND.THETA.LE.T2)GO TO 60
            CALL DIECO1(Z)
            GO TO 70
       60   CALL DIECO2(Z)
       70   CALL CUTDIM(Z)
            X1(J)= XC1+RX1
            Y1(J)= YC1+RY1
            Z1(J)= AL-(RZ1+Z)
            X2(J)=XC2+RX2
            Y2(J)=YC2+RY2
            Z2(J)=AL-(Z+RZ2)
            IF(IC.EQ.1)GO TO 80
            Z=Z-DELZ
            GO TO 150
```

```
C
  90    Z=Z+DELZ
 150   CONTINUE
        IF(IC.EQ.1)GO TO 160
        IF(IC.EQ.2)IC=1
        Z=0
        GO TO 180
 160     IC=2
        Z=AL
 180     CONTINUE
D        CALL PNCHNC(X1,Y1,Z1,NZ1)
         WRITE(5,217)(X1(J),Y1(J),Z1(J),J=1,NZ1)
        WRITE(2'IVAR)(X2(J),Y2(J),Z2(J),J=1,NZ1)
        THETA=THETA+DELT
 200    CONTINUE
        IVAR=1
        DO 220 K=1,NDELTZ
         IF(IQUAD.EQ.1.OR.IQUAD.EQ.2)GO TO 205
        READ(2'IVAR)(X2(J),Y2(J),Z2(J),J=1,NZ1)
        WRITE(5,217)(X2(J),Y2(J),Z2(J),J=1,NZ1)
D        CALL PNCHNC(X2,Y2,Z2,NZ1)
 217    FORMAT(F15.6,1H,,F15.6,1H,,F15.6)
 205     CONTINUE
 220    CONTINUE
         IF(IQUAD.EQ.4) GO TO 230
         X1(1)=X1(NZ1)
         Y1(1)=Y1(NZ1)
         Z1(1)=-1.0
         X1(2)=0.
         Y1(2)=0.
         Z1(2)=Z1(1)
         WRITE(5,210)(X1(J),Y1(J),Z1(J),J=1,2)
D        CALL PNCHNC(X1,Y1,Z1,2)
         GO TO 230
 230     CONTINUE
D        CALL STOPNC
D        CALL LEADER

C***     FLUSH OUTPUT BUFFER
         CALL NCOUT("20,1)
 210     FORMAT(F15.6,2(1H,,F15.6))
         END FILE 2
        STOP
        END
C
        FUNCTION F(K,Z)
C THIS FUNCTION SUBPROGRAM EVALUATES THE FUNCTIONS
C  G(Z),F(Z),H(Z),AND K(Z) WHICH DEFINE THE DIE SURFACE
C K IS A DUMMY INDEX WHICH DETERMINES THE PARTICULAR
C  FUNCTION TO BE EVALUATED
C
        COMMON/DIEPAR/R,AL,A,B,C,D,NDELT,NDELZ
```

```
      GO TO (10,20,30,40,50,60,70,80),K
C
C     FUNCTION G(Z)
   10 F=(R+A)/2.0+((R-A)/2.0)*COS(3.1415927*Z/AL)
      GO TO 90
C
C     FUNCTION F(Z)
   20 F=(R+B)/2.0+((R-B)/2.0)*COS(3.1415927*Z/AL)
      GO TO 90
C
C     FUNCTION H(Z)
   30 F=C/2.0+(C/2.0)*COS(3.1415927*(AL-Z)/AL)
      GO TO 90
C
C     FUNCTION K(Z)
   40 F=D/2.0+(D/2.0)*COS(3.1415927*(AL-Z)/AL)
      GO TO 90
C
C     FUNCTION G'(Z)
   50 F =(-3.1415927/AL)*(R-A)*SIN(3.1415927*Z/AL)/2.0
      GO TO 90
C
C     FUNCTION F'(Z)
   60 F =(-3.1415927/AL)*(R-B)*SIN(3.1415927*Z/AL)/2.0
      GO TO 90
C
C     FUNCTION H'(Z)
   70 F =(3.1415927/AL)*(C/2.0)*SIN(3.1415927*(AL-Z)/AL)
      GO TO 90
C
C     FUNCTION K'(Z)
   80 F =(3.1415927/AL)*(D/2.0)*SIN(3.1415927*(AL-Z)/AL)
      GO TO 90
C
   90 RETURN
      END
      SUBROUTINE DIECO1(Z)
C
C THIS SUBROUTINE SOLVES FOR X AND Y COORDINATES OF A POINT
C ON TOOL PATH FOR GIVEN Z COORDINATE WHEN THETA DOES NOT
C LIE BETWEEN 80 TO 100 DEGREES
      COMMON/DIEPAR/R,AL,A,B,C,D,NDELT,NDELZ
      COMMON/THETAP/THETA,T1,T2
      COMMON/COORD/XC1,YC1,XC2,YC2
      COMMON/CUTTER/RT,RX1,RY1,RZ1,RX2,RY2,RZ2
      FG=F(1,Z)
      FF=F(2,Z)
      FH=F(3,Z)
      FK=F(4,Z)
      SG=FG**2
      SF=FF**2
      SH=FH**2
      SK=FK**2
      T =SIN(THETA)/COS(THETA)
```

```
          A0=SF+SG*T**2.0
          B0=2.0*SF*C+ 2*T*SG*D - 2.0*SF*FH -2.0*T*SG*FK
          C0=SF*C**2.0+SF*SH-2.*SF*FH*C + SG*D**2.0+
     1    SG*SK-2.*SG*D*FK -SF*SG
          D0= SQRT(B0**2 -4.0*A0*C0)
         IF(THETA.GE.-1.0E-5.AND.THETA.LE.T1)GO TO 10
         XC1=(-B0-D0)/(2.0*A0)
         XC2=(-B0+D0)/(2.0*A0)
         GO TO 20
   10    XC1=(-B0+D0)/(2.0*A0)
         XC2=(-B0-D0)/(2.0*A0)
   20    YC1=XC1*T
         YC2=XC2*T
         RETURN
         END
         SUBROUTINE DIECO2(Z)
C
C THIS SUBROUTINE SOLVES FOR X  AND Y COORDINATES OF
C A POINT ON TOOL PATH FOR GIVEN Z COORDINATE WHEN
C THETA LIES BETWEEN 80 TO 100 DEGREES
C
          COMMON/DIEPAR/R,AL,A,B,C,D,NDELT,NDELZ
          COMMON/THETAP/THETA,T1,T2
          COMMON/COORD/XC1,YC1,XC2,YC2
          COMMON/CUTTER/RT,RX1,RY1,RZ1,RX2,RY2,RZ2
           FG=F(1,Z)
          FF=F(2,Z)
          FH=F(3,Z)
          FK=F(4,Z)
          SG=FG**2
          SF=FF**2
          SH=FH**2
          SK=FK**2
          T3=3.1415927/2.0-THETA
         T0=SIN(T3)/COS(T3)
          A0=SG+SF*T0**2.0
          B0=2.0*T0*C*SF-2.0*T0*FH*SF+2.0*D*SG-2.0*FK*SG
          C0=SF*C**2.0+SF*SH-2.*C*FH*SF+SG*D**2.0+
     1    SG*SK-2.0*D*FK*SG-SF*SG
          D0=SQRT(B0**2-4.0*A0*C0)
          YC1=(-B0+D0)/(2.0*A0)
          YC2=(-B0-D0)/(2.*A0)
          XC1=YC1*T0
          XC2=YC2*T0
          RETURN
          END
          SUBROUTINE CUTDIM(Z)
C
```

```
C THIS SUBROUTINE CALCULATES (X,Y,Z) COORDINATES OF
C TOOL RADIUS VECTOR
C
      COMMON/DIEPAR/R,AL,A,B,C,D,NDELT,NDELZ
      COMMON/THETAP/THETA,T1,T2
      COMMON/COORD/XC1,YC1,XC2,YC2
      COMMON/CUTTER/RT,RX1,RY1,RZ1,RX2,RY2,RZ2
C
C
      FG=F(1,Z)
      FF=F(2,Z)
      FH=F(3,Z)
      FK=F(4,Z)
      SG=FG**2.0
      SF=FF**2.0
      SH=FH**2.0
      SK=FK**2.0
      I=1
      X=XC1
      Y=YC1
C
   10 AX=2.0*(X+C-FH)/SG
      AY=2.0*(Y+D-FK)/SF
      AZ= -2.0*((X+C-FH)**2 *F(5,Z)/FG**3.0 +
     1   (X+C-FH)*F(7,Z)/SG + (Y+D-FK)**2.0*F(6,Z)
     2   /FF**3 + (Y+D-FK)*F(8,Z)/SF)
      AW = SQRT(AX**2 +AY**2+ AZ**2)
      IF(I.EQ.2)GO TO 20
      RX1= RT*AX/AW
      RY1= RT*AY/AW
      RZ1= RT*AZ/AW
      I=I+1
      X=XC2
      Y=YC2
      GO TO 10
   20 RX2= RT*AX/AW
      RY2= RT*AY/AW
      RZ2= RT*AZ/AW
      RETURN
      END
*
```

# CHAPTER III

## "COMPUTER-AIDED DESIGN AND MANUFACTURING (CAD/CAM) OF STREAMLINED DIES FOR LUBRICATED EXTRUSION OF SIMPLE STRUCTURAL SHAPES"

## TABLE OF CONTENTS



## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS (Continued)



## LIST OF TABLES

## CHAPTER III

## CAD/CAM OF STREAMLINED DIES FOR LUBRICATED EXTRUSION OF SIMPLE STRUCTURAL SHAPES

### ABSTRACT

This chapter describes the work conducted towards applying CAD/CAM techniques to the extrusion of simple shapes, such as L's, T's, rectangles, and triangles. A numerical technique is described for defining the surface of a "streamlined" die in lubricated extrusion. A theoretical analysis is developed for calculating the mean-extrusion pressure and the mean-pressure distribution on the die surface for the lubricated, as well as for the non-lubricated shape-extrusion processes. To manufacture the "streamlined" dies by Electro-Discharge Machining (EDM), the theoretical basis for Numerical Control (NC) machining of the EDM electrode was outlined. Based on the aforementioned analyses, a system of computer programs called "SHAPE" was developed. SHAPE allows determination of (a) optimal length and shape of the die in lubricated extrusion, (b) shear-zone configuration in nonlubricated extrusion, (c) extrusion load and die-pressure distribution, and (d) cutter paths in NC machining of EDM electrodes. SHAPE can be used in batch, as well as in interactive mode.

A limited number of trials were conducted to evaluate the CAD/CAM techniques developed in this program. For this purpose, round billets from copper 110, aluminum 6063, and aluminum 7075, were extruded using the same extrusion ratio through three types of dies: (1) a streamlined die from round to rectangular, designed and manufactured by CAD/CAM techniques, (2) a flat-faced die from round to rectangular, and (3) a streamlined die from round to round. Results on extrusion loads and metal flow, obtained from the trials, indicated good agreement between predicted and measured values.

### INTRODUCTION

In conventional extrusion of high-strength aluminum alloys, 2000 and 7000 series, flat-faced dies are used. This results in internal shearing and significant temperature increases within the deforming material. Conse-

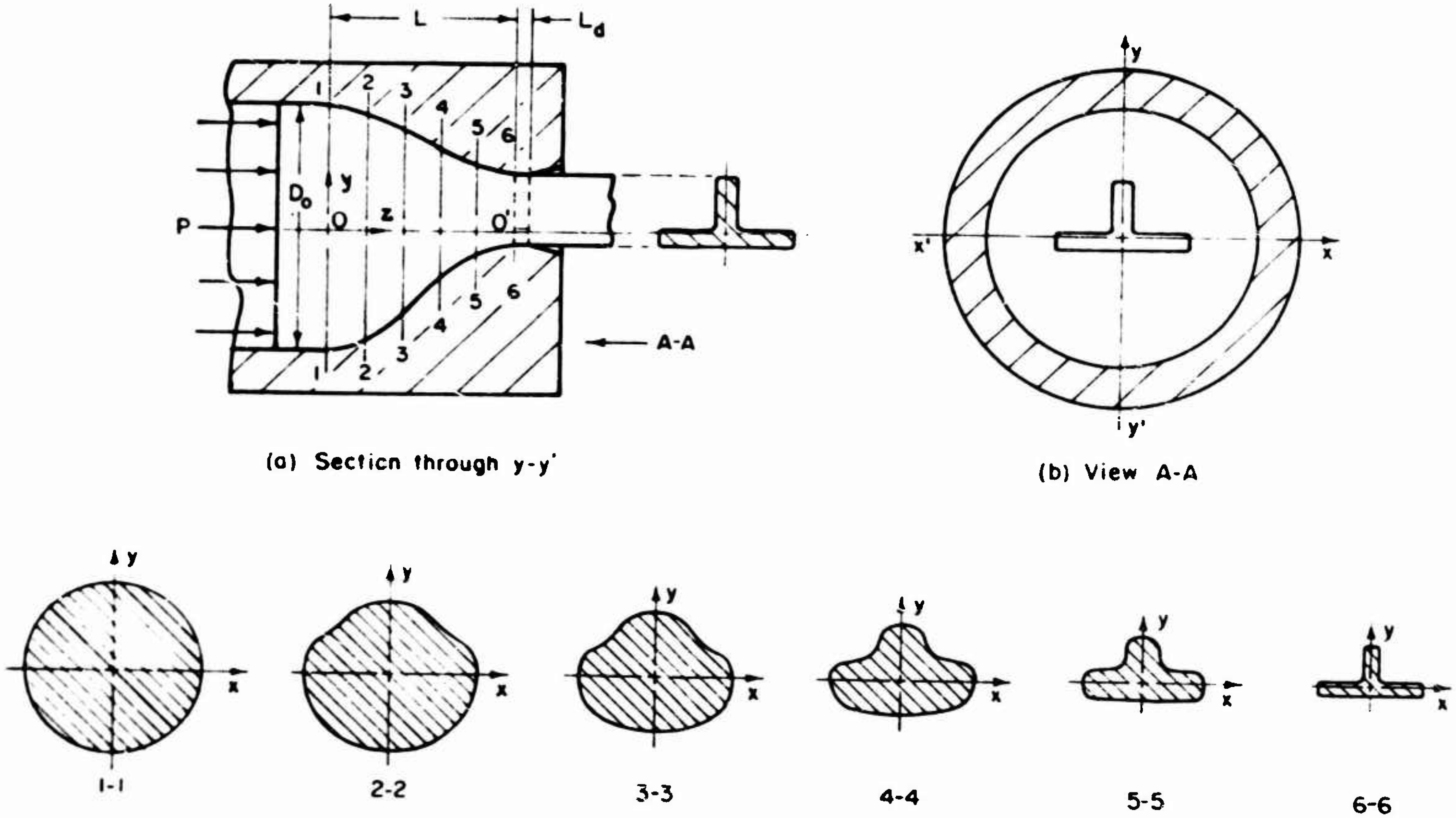
quently, the extrusion must be carried at a sufficiently low speed to avoid hot shortness in the product.[1,2]

Lubricated extrusion of hard-aluminum alloys is expected to increase production rates and to lower the required press capacity to extrude a given product at a predetermined extrusion ratio. In lubricated extrusion of relatively complex shapes, such as U, L, T, I, and others, it is required to use "streamlined" dies which provide a smooth metal flow from the circular container, or billet, to the shaped-die exit. The effective design of such a die must ensure a smooth metal flow and consistent lubrication.[3] One of the primary objectives of the present program is to develop cost-effective computer-aided techniques for designing and manufacturing streamlined dies so that lubricated extrusion can become a practical manufacturing process. The other objective is to apply advanced computer-aided techniques to optimize the conventional lubricated and nonlubricated extrusion processes.

## EXTRUSION OF SIMPLE SHAPES

The design of a "streamlined" die for extruding a "T" shape from a round billet is schematically illustrated in Figure 3-1. The geometry of this die and the variables of the extrusion process should be optimized to (a) give a defect-free extrusion requiring minimum post-extrusion operations (twisting and straightening), (b) require minimum load and energy, and (c) yield maximum throughput at minimum cost.

The process variables to be selected are the speed of the operation, the die geometry, the temperatures of the material and the die, and the frictional conditions at the container-die interface. There is no systematic engineering method which can be used for optimizing the shape-extrusion process. The trial-and-error approach, combined with past experiences, are commonly used in today's industrial practice to obtain satisfactory die and process designs. In the present program, a systematic approach, which utilizes computer-aided techniques, is presented to optimize the lubricated as well as the nonlubricated extrusion processes. The analysis of the mechanics of metal flow, and the calculation of the extrusion load and the die pressures represent the basis for the optimal process design. As a first step in the designing process, the die geometry must be defined. A computerized numerical




(a) Section through y-y'

(b) View A-A

(c) Cross Sections of the Billet During Extrusion

FIGURE 3-1. SCHEMATIC OF A STREAMLINED DIE FOR EXTRUDING A "T" SHAPE

technique is used for this purpose.

## Definition of the Die Geometry

In nonlubricated extrusion of shapes through flat-faced dies, the deforming material shears internally during the initial stages and forms so-called "dead zones" on the flat face of the die. The formation of dead, or nonmoving zones, generates a new "pseudo-die surface" for subsequent flow of the material during the extrusion process. To analyze the steady-state extrusion process, the shape of the dead zones must be predicted, based on the principle that the material deforms such that the rate of energy dissipation is minimum.[4] In analyzing the conventional extrusion of round shapes, the shape of the dead zone can be predicted by calculating the rate of energy dissipation in extrusion through an arbitrarily-shaped die, or through dies of different configurations.[5] The die which requires the minimum extrusion pressure yields the shape of the shear surface. A similar procedure can also be used for predicting the shape of the shear surface in extrusion of nonsymmetric shapes. However, a surface which provides a smooth transition from the initial round billet to the final nonsymmetric shape is too complex to be defined analytically. Therefore, in the present study, a numerical procedure is used for defining the die geometry.

In lubricated extrusion, the die should provide a smooth transition from the circular billet to the final extruded shape. In addition, the die surface should be such that the material undergoes minimum redundant deformation and also exits from the die without bending or twisting. To select the shape of the optimal die, metal flow through dies of different shapes must be analyzed. The optimal die geometry can then be determined by selecting the die configuration which gives the minimum rate of energy dissipation during extrusion. This approach requires that, as a first step, the surface of the streamlined die be defined in a general and arbitrary manner. Again, for structural shapes like T, L, U, and others, it is not possible to describe analytically a die surface which provides smooth transition from a round billet to the desired final shape. Thus, a numerical approach for defining the die surface is necessary for lubricated extrusion, as is the case in nonlubricated extrusion.

Details of the numerical approach, used to determine the die surface, are given in Appendix A. Here, only the procedure is summarized. A primary requirement in the design of the shape-extrusion process is that the extruded material should exit from the die without twisting or bending. This requirement is satisfied if the die shape is such that the extruded material at the die exit has, across its cross section, a uniform velocity in axial direction. Thus, each segment of the original cross section must undergo equal area reduction. The initially circular cross section of the billet is divided into a number of sectors, as shown in Figure 3-2. Starting from a plane of symmetry, the final cross section is divided into the same number of segments. This is done while keeping the extrusion ratios (area of a sector in the billet/area of the corresponding segment in the product) equal to the overall extrusion ratio. Thus,

$$\frac{\text{Area } 012}{\text{Area } 01'2'} = \frac{\text{Area } 023}{\text{Area } 02'3'} \cdots\cdots = \frac{\text{Area } 045}{\text{Area } 04'5'} = \frac{A_o}{A_f}, \qquad (3\text{-}1)$$

where $A_o$ is the billet cross-sectional area and $A_f$ is the cross-sectional area of the rectangular product. According to this construction, the material points at positions 1, 2, 3, 4, and 5 on the boundary $B_o$ of the initial cross section move during extrusion to positions 1', 2', 3', 4', and 5', respectively, on the boundary $B_f$ of the final cross section. Thus, the initial and final positions of the material path lines along the die surface are determined. The path followed by any material point between the initial and final positions is not known. Therefore, arbitrary curves are fitted between corresponding points of the boundaries $B_o$ and $B_f$. These curves define numerically a general die surface, any portion of which can be changed by adjusting the curves fitted in that portion of the surface.

In Figure 3-2, due to symmetry of the extrusion shape, rectangular in this case, no metal flow occurs perpendicular to the extrusion axis 0-0'. Thus, the axis 0-0' is called "neutral axis". For shapes like T and Δ, which have only one plane of symmetry, the position of the neutral axis is determined by a procedure described in Appendix A and summarized here. As shown in Figure 3-3a, the position $x_c$ of plane $x = x_c$ is determined such that the ratio of the area 0'ab to the area 012 is equal to the overall area reduction ($A_o/A_f$) in extruding from round to "T" shape. Thus, b-2 becomes a material path line.

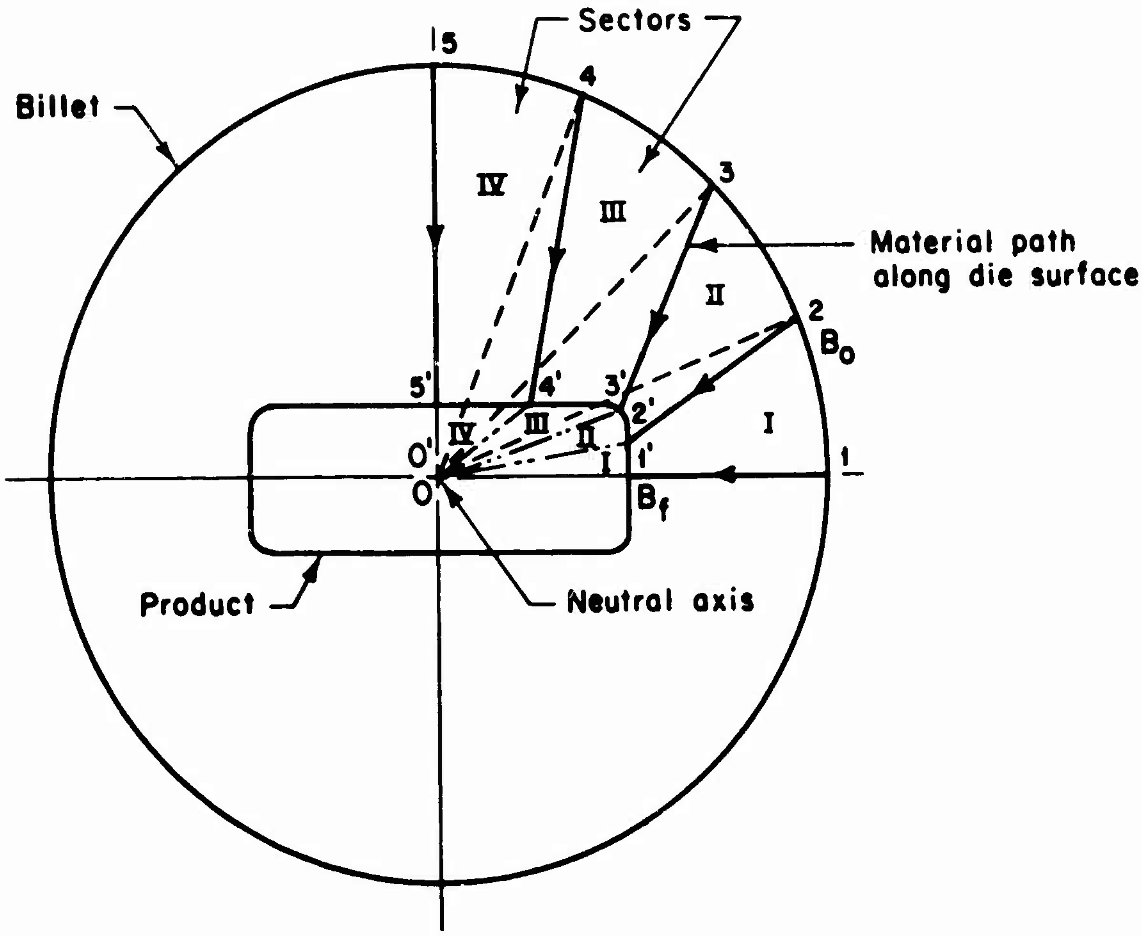
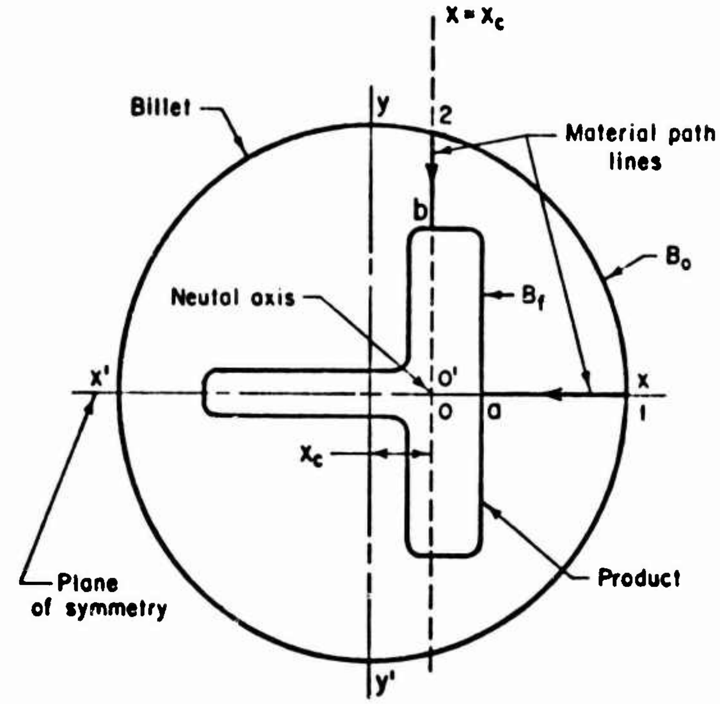
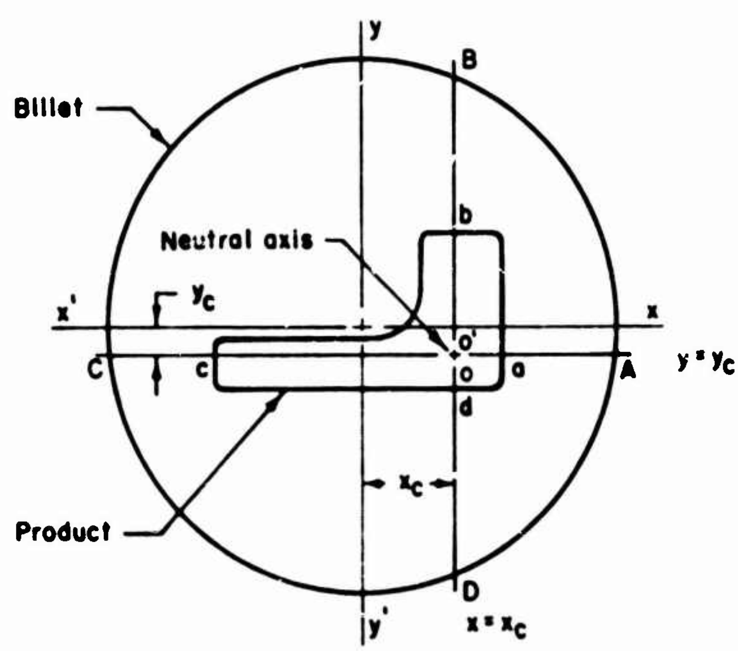



FIGURE 3-2. CONSTRUCTION OF A STREAMLINED DIE SURFACE
IN EXTRUSION OF A RECTANGULAR SHAPE




(a) Extrusion of a "T" shape




(b) Extrusion of an "L" shape

FIGURE 3-3. DETERMINATION OF THE POSITION OF THE NEUTRAL AXIS IN "T" AND "L" SHAPES

The intersection of the plane $x = x_c$ and the plane of symmetry, $y = 0$, gives the position of the neutral axis.

For shapes which do not have any plane of symmetry, like the "L" shown in Figure 3-3b, the position of the neutral axis is determined as follows. The position of plane $x = x_c$ is defined such that the ratio of area ABDA to area abda is equal to the overall area reduction. In a similar way, the position of plane $y = y_c$ is obtained when the ratio of area ABCA to area abca is equal to the overall extrusion ratio. Intersection of these two planes, $x = x_c$ and $y = y_c$, gives the neutral axis 00'.

Once the neutral axis is determined, the initial cross section is divided into a number of sectors starting from the neutral axis at point 0. As before, the final cross section is divided into equal number of triangular segments starting from point 0', while maintaining the area ratios between sectors and corresponding segments equal to the overall extrusion ratio.

Based on the procedure outlined above, a computer program was developed. This program forms a part of the system of programs called "SHAPE", which can be run in interactive as well as in batch mode. In interactive mode, a plot showing billet shape, product shape, neutral axis, material path lines and die cross sections is drawn on CRT (Cathode Ray Tube). During the various stages of plotting, the designer can interact with the program to change, if necessary, the position of the extruded shape with respect to the billet center, and the position of the neutral axis. Figures 3-4 through 3-6 show the die surfaces obtained by the above numerical procedures. The plots were obtained as hard copies of CRT screen displays. Due to the symmetry, only upper halves of the die surfaces are plotted.

## Calculation of Extrusion Load and Die Pressure

To optimize the extrusion process with regard to load and energy requirements, an analysis was developed for calculating the load and die pressure distribution. The knowledge of the total extrusion load and of its components would also help the designer in selecting the extrusion of adequate capacity and in evaluating the overall efficiency of the extrusion process. The mean-die pressure distribution along the die surface is needed to predict the stresses developed in the die during the extrusion process. Thus, this information should help the designer in making appropriate selection of die

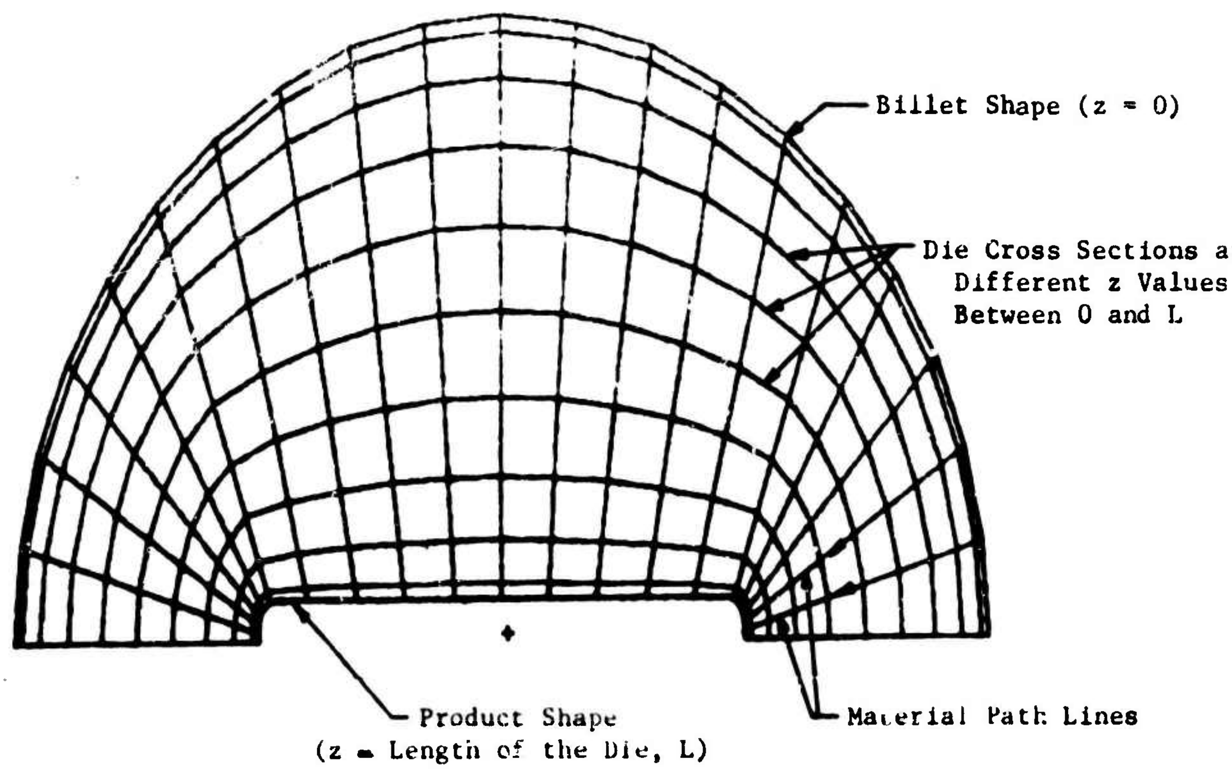



FIGURE 3-4. A STREAMLINE DIE SURFACE FOR EXTRUDING A RECTANGULAR SHAPE FROM A CIRCULAR BILLET

(z is the distance measured along the extrusion axis)

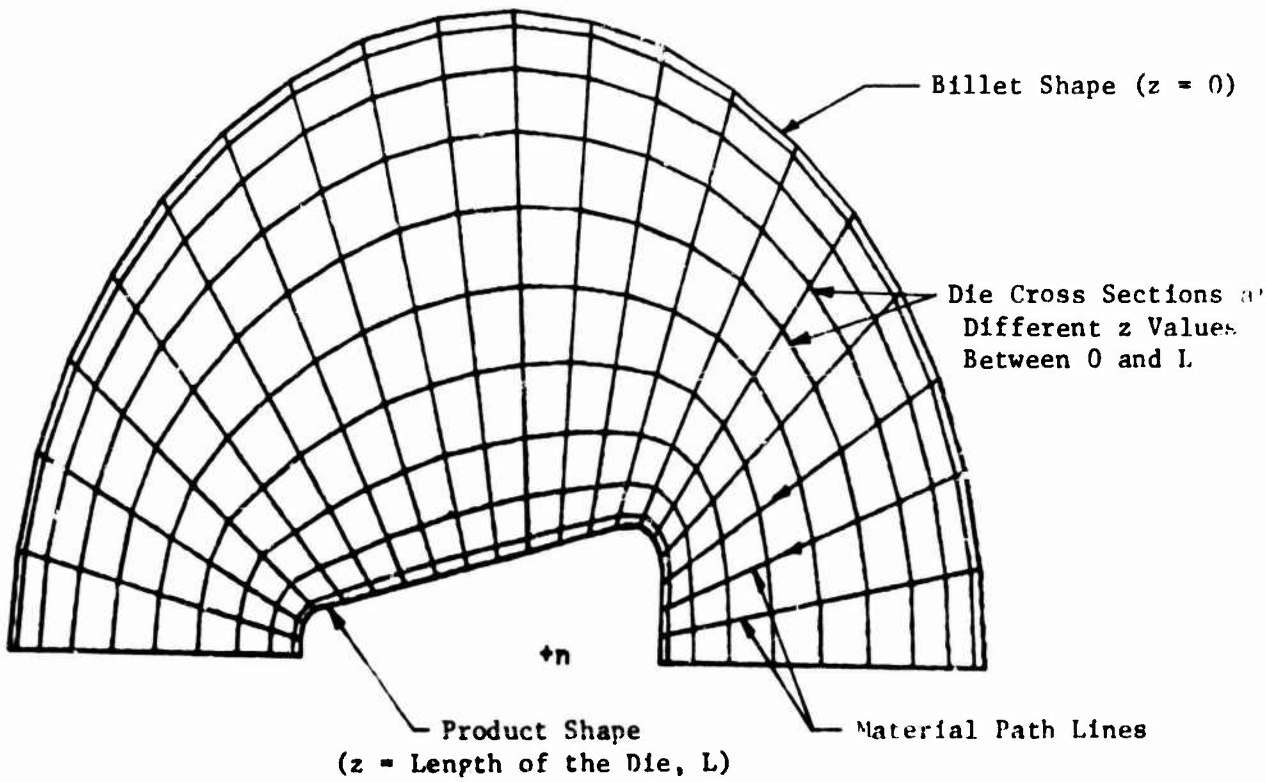



FIGURE 3-5. A STREAMLINE DIE SURFACE FOR EXTRUDING A TRAPEZOIDAL SHAPE FROM A CIRCULAR BILLET

(z is the distance measured along the extrusion axis)

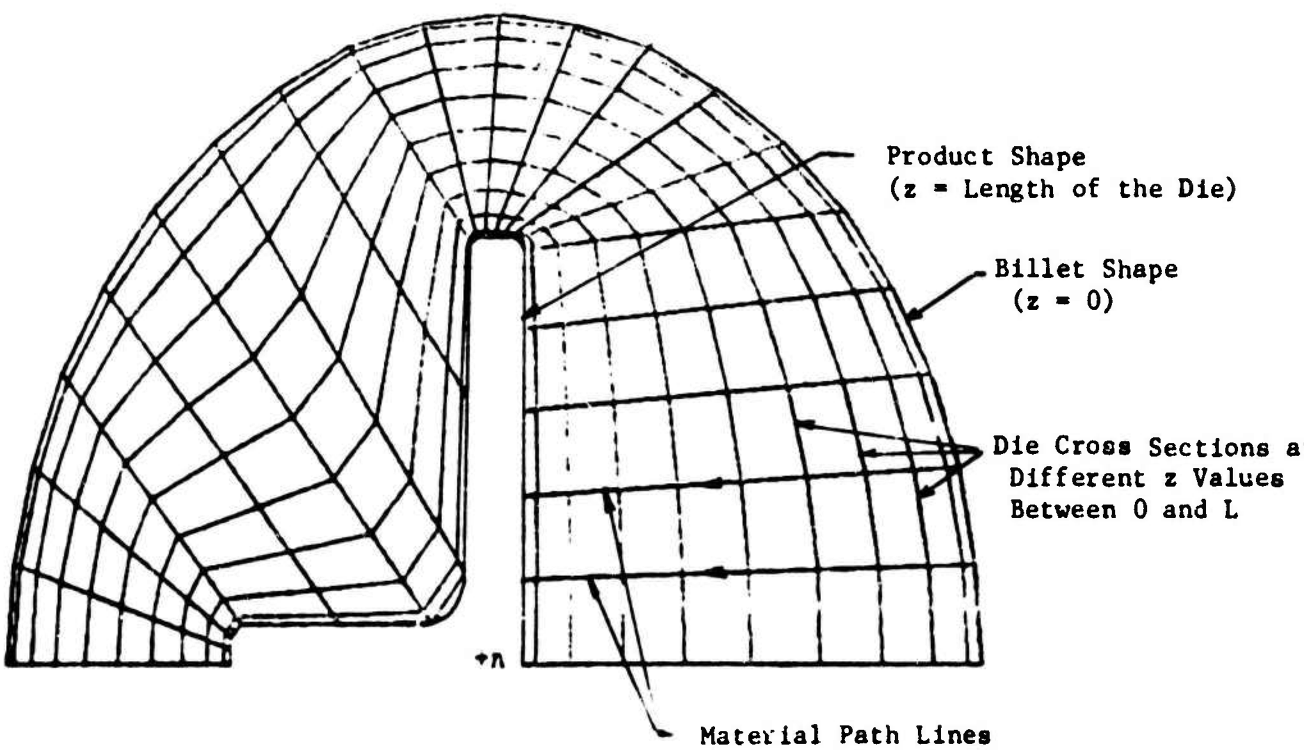



FIGURE 3-6. A STREAMLINE DIE SURFACE FOR EXTRUDING A "T" SHAPE FROM A CIRCULAR BILLET

(z is the distance along the extrusion axis)

material and in avoiding unnecessary premature failure of the dies.

A simple method which is basically an extension of the so-called Siebel's method[6] is used to calculate:

(1) Total extrusion load and the various components that make up this load

(2) Distribution of mean-die pressure along the die surface in axial direction.

The total extrusion pressure $P_{avg}$ is given as the sum of its components by

$$P_{avg} = P_{fc} + P_{id} + P_{sh} + P_{fd} + P_{fl} , \qquad (3\text{-}2)$$

where
$P_{fc}$ = component of pressure due to friction in container
$P_{id}$ = component of pressure due to internal plastic deformation for area reduction
$P_{sh}$ = component of pressure due to shear deformation at entrance and exit of the die
$P_{fd}$ = component of pressure due to friction at die surface
$P_{fl}$ = component of pressure due to friction at die land.

The various pressure components are determined using the basic theory of plasticity. The pressures due to friction at the container and the die surfaces are determined by assuming the interfacial friction stress ($\tau$) to be given by:

$$\tau = m \frac{\bar{\sigma}}{\sqrt{3}} . \qquad (3\text{-}3)$$

$\bar{\sigma}$ is the flow stress of the material at the interface and m is the friction shear factor for a particular interface. m is taken to be constant for given conditions of lubrication, billet material, temperature, and die material. The details of the analysis are given in Appendix B. From the total extrusion pressure, the total extrusion load is determined by the relation:

$$\text{Total Extrusion Load} = \frac{\pi}{4} D_o^2 P_{avg} , \qquad (3\text{-}4)$$

where $D_o$ is the initial diameter of the billet.

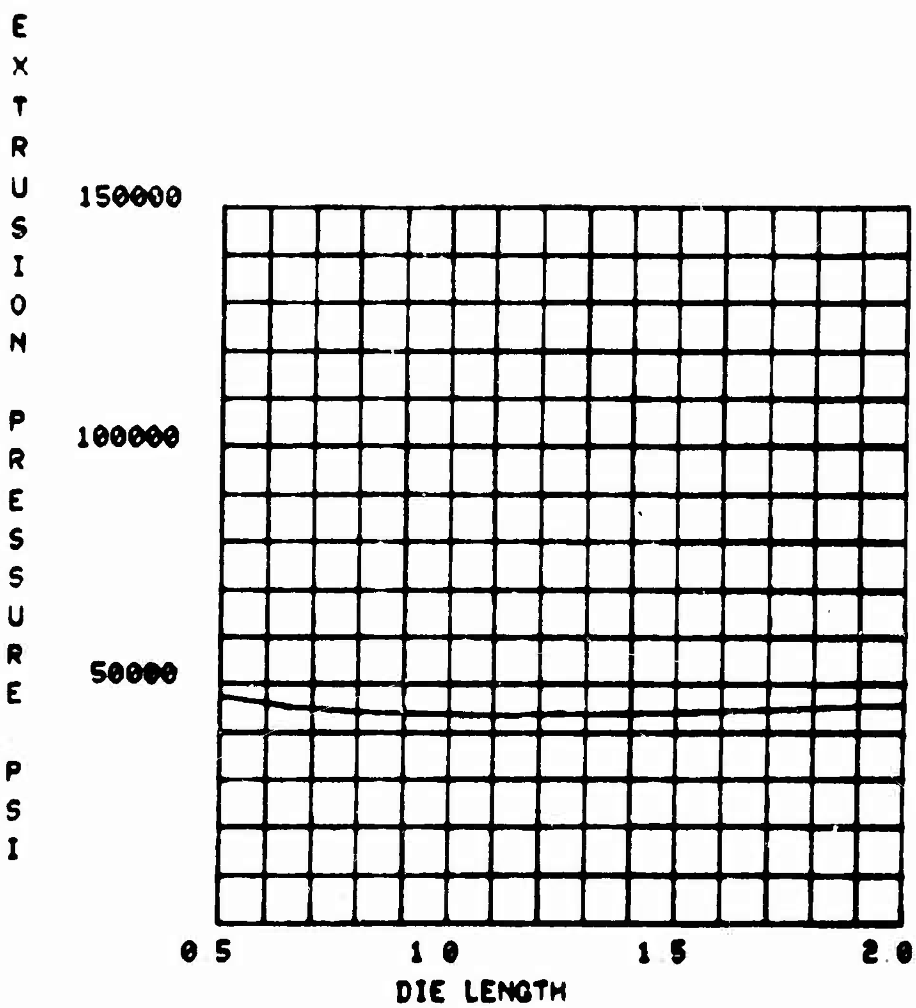
The die pressure distribution is calculated using the condition that the mean-extrusion pressure at any cross section of the billet can be approximated by the pressure required to extrude the portion of billet between that

section and the die exit.[7] Knowing this pressure, the mean pressure acting on the die at any cross section can be determined from the plasticity condition, as described in Appendix B.

The load and the pressure distribution are obtained as function of the process variables like initial billet diameter, initial billet length, speed of the extrusion press, final extrusion shape, area reduction, type of die (flat face or streamlined), friction at container and die surfaces, temperature, and flow properties of the material being extruded. For given values of these process variables, the extrusion load is calculated numerically. Special computer programs, developed for this purpose, form a part of system of programs "SHAPE".

For lubricated extrusion, the streamlined die surface is defined according to the procedure discussed earlier and then the load is calculated. In case an optimal die length (or height) is to be determined, the extrusion pressure is calculated for different die lengths. In batch mode, the die length which requires minimum extrusion pressure is selected. In interactive mode, the extrusion pressure is plotted on CRT as a function of the die length. Also, the numerical values of pressure and die length are printed. The designer can use his judgment to select the optimal die length, which he then enters through the keyboard for further load calculation. Figure 3-7 shows, as an example, a plot of extrusion pressure versus the die length, obtained as a hard copy of the CRT screen display. The reason for selecting a die length which may not require minimum pressure is that the minimum pressure is not the only consideration in selecting an optimal length. Other factors, such as keeping the die length short to have small discard and reducing the cost of manufacturing the dies, must also be considered. In the interactive mode, the designer can select the die length based on his judgment of the relative importance of all these factors.

In nonlubricated extrusion through flat-faced dies, the material shears internally and forms a dead zone at the entrance face of the die during initial stages of the extrusion process. A new "pseudo-die surface" is thus created for subsequent extrusion. To calculate the extrusion load, it is assumed that the general configuration of the shear surface is the same as that of the optimal die for lubricated extrusion, with the difference being that the determination of the "pseudo-die" length is based on the maximum shear factor ($m_d$) at the "pseudo-die" surface. The interative procedure,




| Die Length | Extrusion Pressure psi |
|---|---|
| 0 65 | 45222 6 |
| 0 80 | 44182 4 |
| 0 95 | 43725 3 |
| 1.10 | 43612 8 |
| 1 25 | 43720.9 |
| 1.40 | 43978.6 |
| 1.55 | 44342.6 |
| 1.70 | 44784.6 |
| 1 85 | 45285 8 |
| 2.00 | 45832.8 |

FIGURE 3-7. MEAN EXTRUSION PRESSURE VERSUS DIE LENGTH CALCULATED FOR EXTRUDING A RECTANGULAR SHAPE FROM A ROUND BILLET

(Process Conditions as Specified in Table 1)

discussed earlier, is used to calculate the optimal die length for $m_d = 1$ and this length is then used for calculating the extrusion load for nonlubricated extrusion process.

As an illustration, Table 3-1 shows the input and output obtained from the computer program "SHAPE" for a specific case. As input, the material code (IMATER) specifies the material to be extruded and die-curve code (NCURVE) specifies the type of curve fitted between initial and final positions of a material path line, as discussed previously. In interactive mode, the mean die pressure distribution along the axial direction, z, is plotted on CRT. A hard copy of the CRT display is shown in Figure 3-8.

## Manufacturing of the Extrusion Dies

For lubricated extrusion, the streamlined dies have complex surfaces as shown in Figure 3-4. Since conventional methods like copy turning or milling cannot be used, the only practical and economical method of manufacturing such dies is the Electro-Discharge Machining (EDM). In this process, the appropriate surface is machined on an electrode made of graphite or copper. This electrode is then used to EDM the rough-machined die block to generate the desired surface.

In our case, the die surface is defined as an array of points in a three-dimensional space, as shown in Figure 3-4 through 3-6. Standard APT (Automatically Programmed Tools) and other standard systems for NC machining cannot be readily used to generate the necessary tape for machining of the die surface. Therefore, a special procedure was developed for NC machining of the EDM electrodes. The details, including the theoretical basis of the procedure, are explained in Appendix C. A short description is included here.

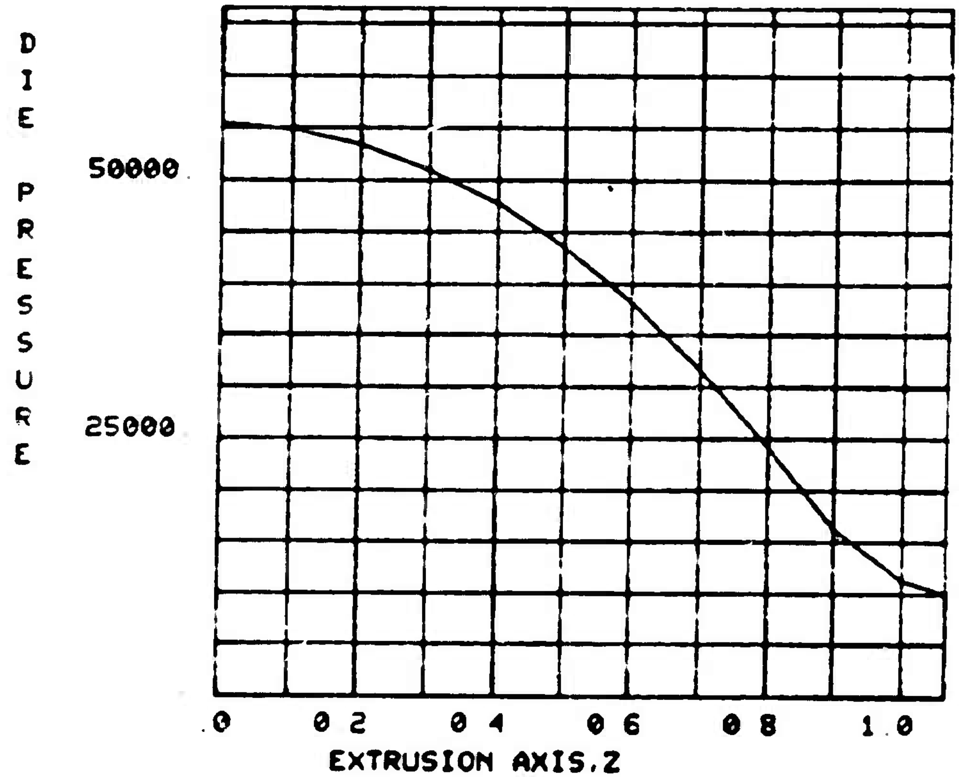
For machining the surface by NC, the paths of the cutting tool as it machines the surface should be determined. If a ball-end mill is used, the position of the center of the spherical portion, with respect to any given point on the surface, can be determined by constructing a vector normal to the surface at that given point. In our case, the normal vector is calculated from the cross product of two vectors; one tangent to the surface along the material path line, and the other tangent to the cross-sectional boundary. For a tool of given radius, the coordinates of the cutter paths are determined as the tool moves, in a predetermined manner, over the array of points defining the die surface.

TABLE 3-1. INPUT AND OUTPUT INFORMATION FROM THE COMPUTER PROGRAM "SHAPE" ON LOAD AND DIE PRESSURE DISTRIBUTION

(A Rectangular Shape is Extruded from a Round Billet)

```
          INPUT
RADIUS OF THE BILLET (IN)         .RAD  =     1 500
INTIAL TEMPERATURE OF THE BILLET (F) =      800 000
SPEED OF THE RAM (IN/SEC)         .VO   = [illegible] 000
LENGTH OF THE BILLET (IN)         .LO   =     6 000
LENGTH OF THE DIE LAND (IN)       .LD   =     0.061
FRICTION SHEAR FACTOR AT CONTAINER.MC=      0.200
FRICTION SHEAR FACTOR AT DIE        .MD=      0.300
MATERIAL CODE,                  IMATER  =         8
DIE CURVE CODE,                 NCURVE  =         1
POINTS DEFINING EXTRUSION SHAPE
         X                Y               R
      0 7500            0000            0000
      0 7500          0 1000          0.0500
     -0 7500          0 1000          0.0500
     -0 7500            0000            0000


          OUTPUT
CROSS-SECTIONAL AREA OF THE BILLET.AO=      7 069
CROSS-SECTIONAL AREA OF EXTRUSION .AF=      0 297
                    AREA RATIO (AO/AF)=    23 760
POSITION OF THE NEUTRAL AXIS        .XC=    0 019
                                     YC=     .000
POSITION OF THE EXTRUDED SHAPE WITH
RESPECT TO THE BILLET AXIS        XMOV=      000
                                  YMOV=      .000
PERIMETER OF THE EXTRUSION SHAPE       =    3.299
DIE LENGTH  .OPTIMAL OR SELECTED       =    1.000
VOLUME OF MATL IN THE DIE              =    3.307
SURFACE AREA OF THE DIE                =    9.556
COMPONENT OF EXTRUSION PRESSURE
DUE TO PLASTIC DEFORMATION             = 31780.176
DUE TO SHEAR AT DIE ENTRANCE AND EXIT  =     0.000
DUE TO FRICTION AT CONTAINER           =  8510.326
DUE TO FRICTION AT DIE SURFACE         = 12625.306
DUE TO FRICTION AT DIE LAND            =  1171 507
TOTAL MEAN EXTRUSION PRESSURE          = 54087.315
        TOTAL EXTRUSION LOAD           = 381[illegible].6
```




| Z | DIE PRES |
|---|---|
| .00 | 55517 0 |
| 0.10 | 54878 6 |
| 0.20 | 53390.4 |
| 0.30 | 51017 0 |
| 0.40 | 47717 5 |
| 0.50 | 43442 4 |
| 0 60 | 38129 6 |
| 0.70 | 31712.0 |
| 0 80 | 24204 9 |
| 0 90 | 16263 0 |
| 1.00 | 11171.5 |
| 1.06 | 13000 0 |

FIGURE 3-8. MEAN DIE PRESSURE DISTRIBUTION ALONG THE DIE SURFACE IN THE DIRECTION OF EXTRUSION FOR THE PROCESS CONDITIONS SPECIFIED IN TABLE 1

Based on the above procedure, special-purpose FORTRAN programs are written. These programs also form a part of the system of programs called "SHAPE". In SHAPE, special routines are included to check for undercutting or gouging by the cutter.

In interactive mode, the calculation of the cutter positions and the plotting of these positions on CRT are done simultaneously. If undercutting is detected, the program stops momentarily and a warning is displayed on the CRT screen. The designer has then the option of reducing the size of the tool, or proceeding with the program, or stopping it. Figure 3-9 shows an example plot of cutter paths for machining an EDM electrode for a round-to-rectangle extrusion die.

## Analysis of the Shape-Extrusion Process by the Computer Program "SHAPE"

As stated earlier, the procedure of defining the die surface, the analysis to calculate the extrusion load and pressures, and the procedure for NC machining of the EDM electrode for the die are incorporated in a set of computer programs called "SHAPE", which can be used in batch or interactive mode. Thus, SHAPE analyzes the extrusion of simple shapes and prepares the necessary output for optimal design of the extrusion process. The following are the capabilities and salient features of SHAPE:

- Determination of the optimal length and the die configuration in lubricated extrusion
- Calculation of the shape of the shear zone in nonlubricated extrusion of simple shapes
- Calculation of the extrusion load and the mean-die pressure distribution
- Calculation of other pertinent information, such as area reduction in extrusion, the perimeter of the extruded shape, and the flow stress of the extruded material
- Calculation of the cutter paths for NC machining of the EDM electrode for manufacturing the extrusion die.

The following are the limitations of SHAPE in its present form and the suggested future improvements:

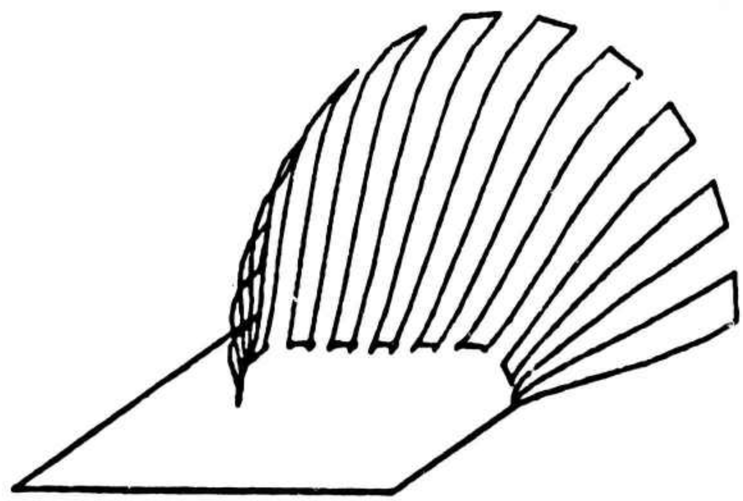


FIGURE 3-9. CUTTER PATH IN NC MACHINING OF EDM ELECTRODE

(1) In its present form, SHAPE can handle only relative simple extruded shapes, such as round, rectangular, triangular, hexagonal, or similar shapes with no re-entrant angles. In addition, it can handle shapes like T, Z and L to a limited extent. This limitation of SHAPE can be removed as the work progresses and additional information on metal flow in streamlined extrusion becomes available. It is expected that, in the final form, SHAPE will be capable of handling all structural shapes used for structural aircraft applications.

(2) SHAPE has been coded primarily for the lubricated extrusion process although a good part of it can also be used for analyzing the nonlubricated extrusion process through flat-face dies. SHAPE does not include, in its present form, information on design of die-land variation which is an important part of designing the nonlubricated extrusion process. Pertinent information of empirical nature on this subject is available. This information, together with some additional theoretical effort on the subject, will be used to make SHAPE applicable for conventional nonlubricated extrusion processes as well.

(3) In the die design, SHAPE does not include any basis for positioning a nonsymmetric part with respect to the billet axis. Empirical information, together with some theoretical and experimental effort on this subject will be used to formulate a suitable basis.

(4) Theoretical and conceptual basis used in coding SHAPE should be expanded and modified.

Appendixes D and E give information on the programming aspects of "SHAPE".

## EXTRUSION TRIALS

In a limited scale, extrusion trials were conducted to achieve the following objectives:

(1) To evaluate the CAD/CAM techniques developed in the program and improve them as necessary, based on trial results. The computer-aided design (CAD) techniques allow the theoretical prediction of the total extrusion load and its components, and the characteristics of metal deformation. In extrusion trials, load and the metal flow at the die surface were measured to check the validity of the theoretical predictions. Computer-aided manufacturing (CAM) techniques, developed in this program, were used to manufacture the streamlined die for extruding a rectangular shape. Dimensions of the die surface were measured to ascertain the correctness of the computer programs.

(2) To make a preliminary evaluation of the lubricated extrusion of aluminum alloys, trials were conducted in lubricated extrusion through streamlined dies and in conventional non-lubricated extrusion through flat-face dies. These trials highlighted the process parameters, which are critical for the success of the lubricated-extrusion process.

It may be mentioned here that in order to evaluate the lubricated extrusion process, the conventional materials, Al 7075, Al 6063 and Cu 110, were substituted for the model materials, plasticine and lead, which were selected originally at the start of the program for conducting model studies.

### Outline of Extrusion Trials

A summary of the process variables investigated in lubricated and non-lubricated extrusion trials is given in Table 3-2.

The trials were performed in a 700-ton hydraulic press, in cooperation with the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio. A detailed description of the extrusion procedures and equipment is given in Reference (14).

TABLE 3-2. SUMMARY OF PROCESS CONDITIONS INVESTIGATED IN THE EXTRUSION TRIALS

| | |
|---|---|
| **Billet:** | |
| Materials: | Cu 110, Al 6063, Al 7075 |
| Size: | 3-inch diameter x 5-1/2-inch long |
| Nose Configuration: | Flat for nonlubricated extrusion and 1/2-inch long curved, angle or radiused lead for lubricated process |
| Lubrication: (where applicable) | Cu 110: polygraph, sprayed<br>Al 6063 and Al 7075: Acheson 907 dipped or Felpro C300 sprayed |
| Temperature: | Cu 110: 1200 F<br>Al 6063: 750 F, 600 F<br>Al 7075: 750 F |
| **Die:** | |
| Design: | (1) Curved -- round to round<br>(2) Flat faced -- round to rectangle<br>(3) Streamlined -- round to rectangle |
| Material: | H11, H13 |
| Lubrication: (where applicable) | Fiske 604 D |
| **Product:** | (1) 0.685-inch diameter round rod<br>(2) 2 x .186-inch rectangular bar with 1/16-inch radius at the corners |
| **Extrusion Ratio:** | 19.2:1 |
| **Press:** | |
| Capacity: | 700 tons (peak) |
| Type: | horizontal-hydraulic press |
| Container: | 3.072-inch diameter |
| Ram Speed: | 20-900 inch/mt |

The press is fully instrumented to measure the total extrusion force on the stem, the force on the die, the position of stem during extrusion, and the ram velocity.

Extruded Shapes

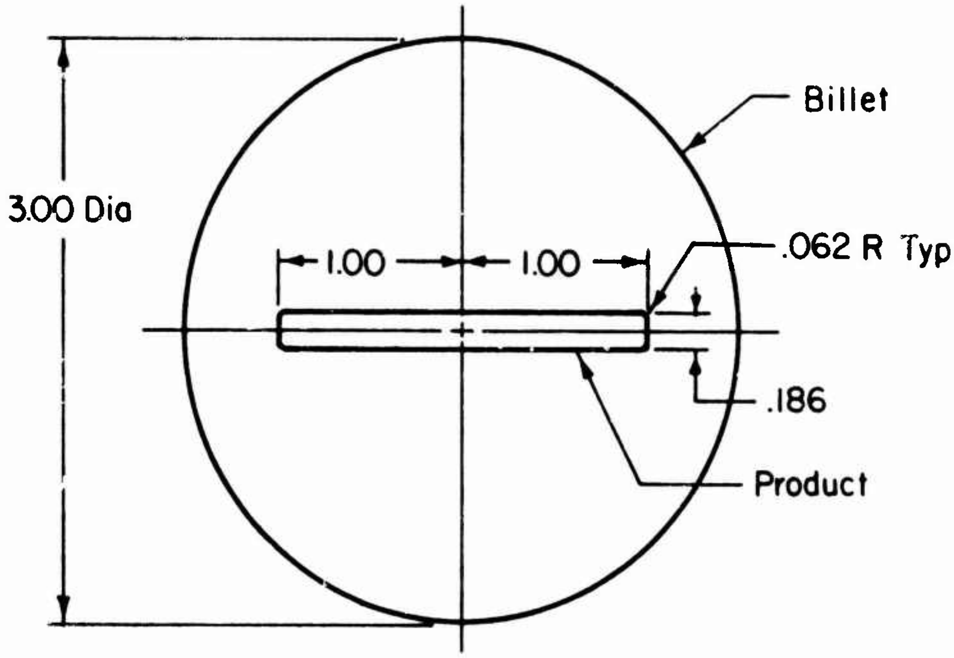
A round-cornered rectangle and an axisymmetric round were the two shapes extruded in this program.

A round-cornered rectangle was chosen since the rectangle can be used as a module to form most of the extruded-structural shapes used in military hardware. The round shape was extruded under similar conditions as the rectangular shape, in order to evaluate the effects of extrusion and die geometries on load and metal flow. Figure 3-10 gives the dimensions of the extruded shapes.

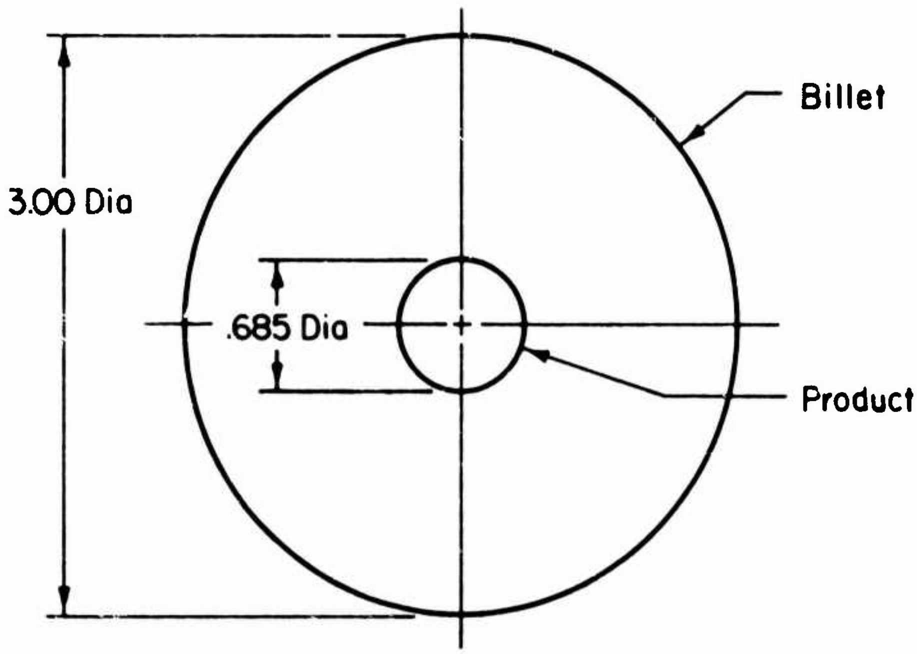
Billet Materials and Preparation

The materials extruded were copper 110 and aluminum alloys 6063 and 7075. Copper 110 was extruded to study the metal flow under lubricated conditions. This alloy is much easier to lubricate compared to Al 6063 and Al 7075. It was felt that with Cu 110, the metal flow along the die surface would not be affected by die pick-up problems associated with extrusion of aluminum alloys. Aluminum alloy 6063 was extruded to establish the procedure for lubricated extrusion of Al 7075. As stated before, there are no established procedures for lubricated extrusion of Al 7075. The conventional practice is to extrude this material without any lubrication of the billet and with some lubrication on the die surface to ensure the separation of the die from the rest of the billet after extrusion. Al 6063 is softer and easier to extrude compared to Al 7075, and it is extruded at about the same temperature as Al 7075. Extruded structural parts for military applications are primarily made of hard-aluminum alloys of 2000 and 7000 series (mostly Al 2024 and Al 7075). Al 7075 was chosen as representative of these hard-aluminum alloys.

Table 3-3 gives the heat treatment of the billet stock prior to machining as well as the nose configuration of the machined billets used in the trials. All billets had 2.993 ± 0.003-inch diameter and approximately 5.5-inch length.




(a) Rectangular shape from a round billet.
Area reduction ≃ 20:1.




(b) Round shape from a round billet. Area reduction ≃ 20:1.

FIGURE 3- RECTANGULAR AND ROUND SHAPES EXTRUDED IN THE TRIALS

TABLE 3-3. BILLETS USED IN EXTRUSION TRIAL

| Billet No. | Material | Nose Configuration[a] | Condition | Lubrication[b] | Remarks |
|---|---|---|---|---|---|
| 1 | Al 7075 | Flat | Annealed | None | The wrought 3-1/2-inch diameter billet stock was annealed in the following manner: (1) Heated at 775 F for 3 hours and cooled in still air, and (2) heated at 450 F for 5 hours and cooled in still air. |
| 3 | Al 7075 | NC Lead | Annealed | Acheson 907 | |
| 5 | Al 7075 | 3/8 R Lead | Annealed | C300 | |
| 6 | Al 7075 | NC Lead | Annealed | C300 | |
| 7 | Al 6063 | Angle Lead | Annealed | C300 | No heat treatment. Billets were machined from homogenized cast bar provided by Alcoa (Aluminum Company of America). |
| 8 | Al 6063 | 3/8 R Lead | Annealed | Acheson 907 | |
| 9 | Al 6063 | NC Lead | Annealed | Acheson 907 | |
| 10 | Al 6063 | Flat | Annealed | None | |
| 11 | Al 6063 | 1/4 R Lead | Annealed | C300 | |
| 12[c] | Cu 110 | 1/4 R Lead | Annealed | Polygraph | None |
| 13 | Cu 110 | Flat | Annealed | Polygraph | |

(a) Nose configuration:

Flat: 1/16 R corner radius on billet.
NC Lead: 1/2 inch of the billet nose was machined to the streamlined die surface.
1/4 R Lead: Billet nosed radiused 1/4 inch.
Angle Lead: 1/2 inch of billet nose chamfered 10°.

(b) Lubricant Felpro C300 was sprayed on, polygraph was brushed on, and Acheson 907 was applied by dipping billets in Acheson 907 solution.

(c) Longitudinal and circumferential lines spaced approximately 1/2 inch and 0.010 deep were marked on the billet to observe metal flow.

Die Designs

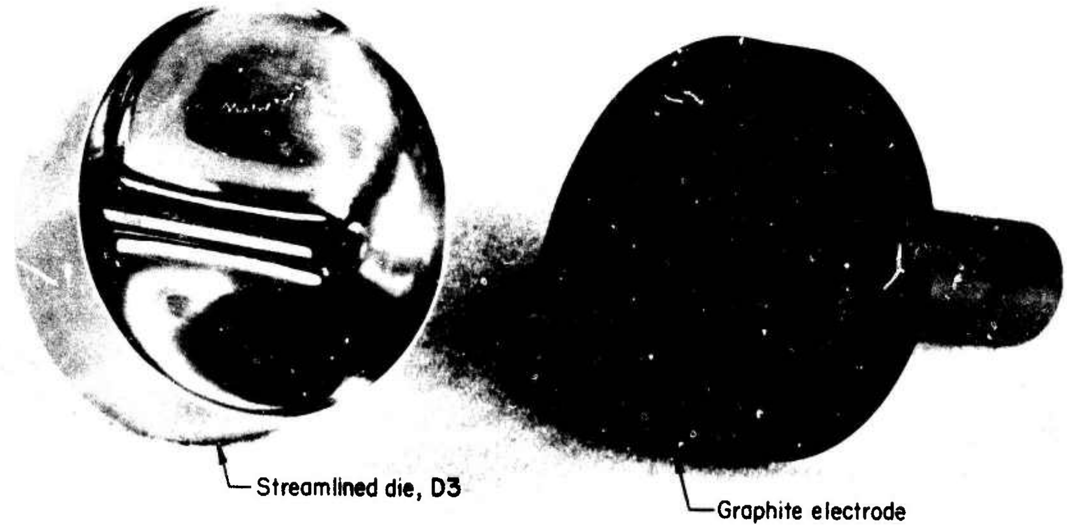
Figure 3-11b shows the three extrusion dies used in extruding rectangular and round shapes.

For the lubricated extrusion of the rectangular product, a streamlined die was manufactured using "SHAPE", the system of computer programs discussed earlier. The streamlined die has a curved surface which provides a smooth transition from the round to rectangle shape. The die was made by EDM process. The necessary tape for NC machining of graphite electrode was prepared using "SHAPE". The electrodes were machined on an NC (Numerical Control) machine at Battelle. Figure 3-11a shows a photograph of the graphite electrode and the streamlined die.

A flat-faced die was made for the nonlubricated extrusion of the rectangular shape. For extruding the round shape, a curved die was also fabricated, Figure 3-11b. All the three dies were dimensioned to give an area reduction of 19.2. Detailed dimensions and the procedure of manufacturing the dies are given in Appendix F.

Billet and Die Lubrication

Based on the previous experience at Battelle on lubricated extrusion of aluminum alloys, Acheson 907 was selected initially as the billet lubricant. This lubricant is said to be tenacious and suitable where the lubricated surface is stretched extensively as in extrusion of shapes. However, after the first set of trials, the billet lubricant was changed to Felpro C300. Prior experience in extruding aluminum alloys was that the lubrication system of Felpro C300 on billet and Fiske 604D on die and container had worked quite well in past studies. For Cu 110, polygraph was selected, based on existing extrusion practice. The container and the die were lubricated with Fiske 604D.




(a)

Flat-faced die
D1

Streamlined die
(round to rectangle)
D3

Curved die
(round to round)
D2

(b)

FIGURE 3-11. DIES USED IN EXTRUSION TRIALS

## Results of Extrusion Trials

The process conditions and the results of the extrusion trials are listed in Table 3-4. In most trials, billets were extruded partially, and small butts were left unextruded to observe billet lubrication and metal flow.

In the first set of trials, billets numbered 8, 3, 9, 10 and 1 were extruded. Considerable die pick was observed in lubricated extrusion of aluminum alloys. The die pickup was obviously due to the breakdown of lubrication. Upon evaluation of the shape of the butt, this lubrication breakdown was attributed to the presence of the die lip, shown in Figure 3-12a, which scraped the billet material near the billet surface.

Figure 3-12a illustrates the tooling arrangement which caused lubrication breakdown. The die sits freely in the container and has the die lip in front of the billet. The lubrication breaks down when the lubricated billet surface is either sheared by the lip, or deformed severly and possibly forming a dead zone. It is obvious that with the present die-container arrangement, it is not possible to completely eliminate this problem. After evaluating the results of the first set of trials, it was concluded that the pickup could be minimized by (1) modifying the die lip to a very thin and sharp edge, and (2) by replacing Acheson 907, which contains polymers and does not dry completely, with Felpro C300 as the billet lubricant. Previous experiences had shown Felpro C300 to be quite effective in lubrication of aluminum alloys.

Based on the above evaluation, the dies D2 and D3 were modified as shown in Figure 3-12b. Also, Felpro C300 was used as the billet lubricant in the subsequent trials. Table 3-4 also shows the results of extrusions conducted after making these changes. Although die pickup was no longer severe, a thin foil, probably sheared by the sharp lip of the die, was found in between the surface of the die and the butt. The possible shearing of the billet surface by the die lip cannot be eliminated without making a major change in the tooling arrangement, or in the die dimensions, used in the present trials. Therefore, it was decided not to undertake any major change in tooling and to terminate these preliminary trials, based on two considerations:

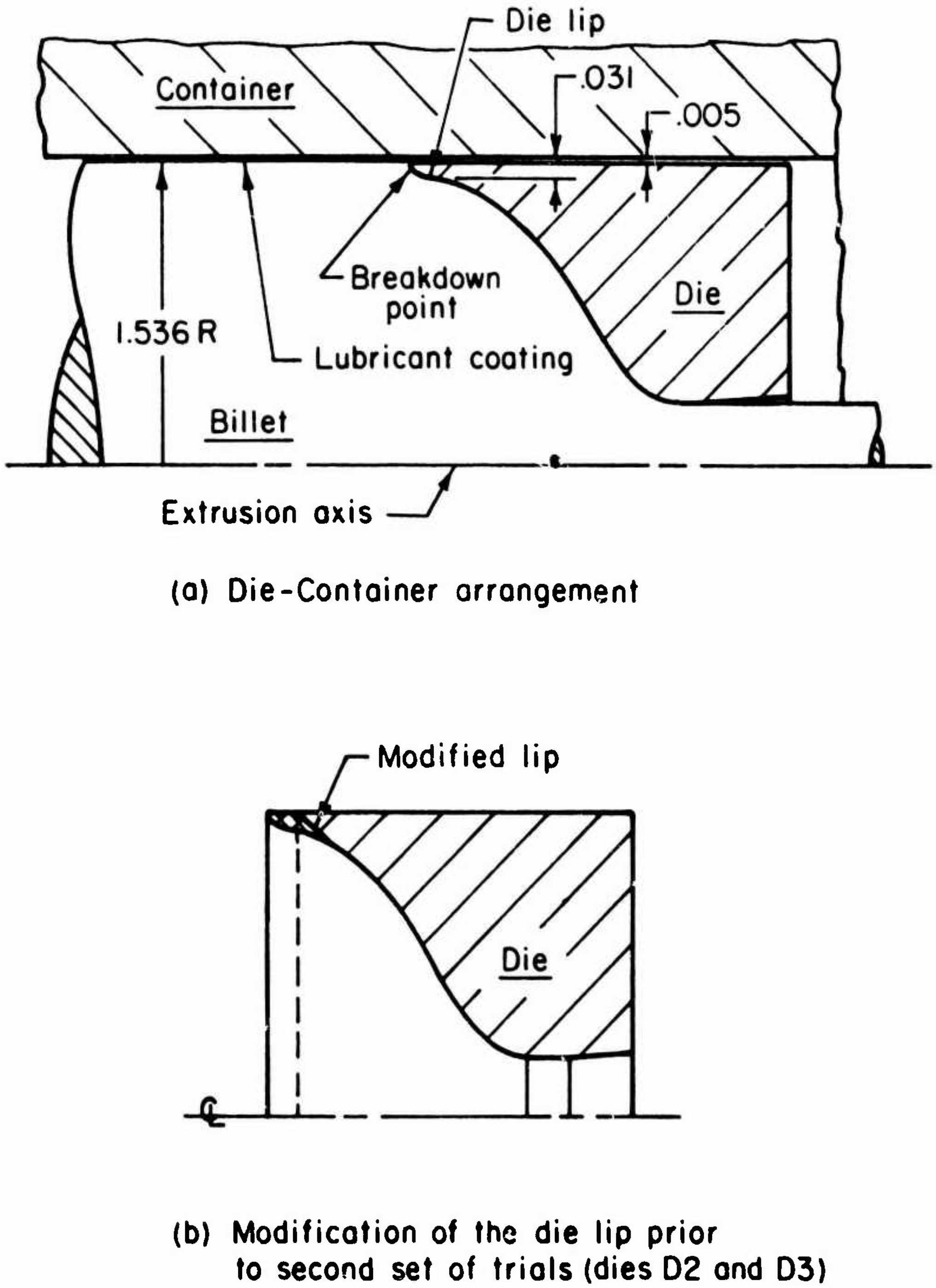



FIGURE 3-12. ILLUSTRATION OF THE DIE-CONTAINER ARRANGEMENT AND THE DIE CONFIGURATION CAUSING LUBRICATION BREAKDOWN

TABLE 3-4. RESULTS OF EXTRUSION TRIALS CONDUCTED AT AFML

| Billet No. | Billet Material | Billet Lubrication | Die(a) | Ram Speed in/sec | Billet Temperature °F | Product Finish | Extrusion Pressure, ksi | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Maximum | Mimimum | Remarks |
| **First Set** | | | | | | | | | |
| 8 | Al 6063 | Acheson 907 | D2 | 1.0 | 750 | good; some striations | 53 | 46 | Die pickup |
| 3 | Al 7075 | Acheson 907 | D3 | 0.5 | 750 | Excellent | 86 | 81 | Die cracked; die pickup |
| 9 | Al 6063 | Acheson 907 | D3 | 0.4 | 750 | Good | 59 | 59 | Die pickup |
| 10 | Al 6063 | None | D1 | 0.4 | 750 | Excellent | 54 | 51 | -- |
| 1 | Al 7075 | None | D1 | 0.4 | 750 | Excellent | 86 | 84 | -- |
| **Second Set** | | | | | | | | | |
| 13 | Cu 110 | Polygraph | D1 | 1.95 | 1200 | Good | 85 | 74 | -- |
| 12 | Cu 110 | Polygraph | D3 (modified) | 2.35 | 1200 | Good | 78 | 77 | A thin foil on the surface of the butt |
| 11 | Al 6063 | C300 | D2 (modified) | 2.05 | 600 | Good | 54 | 49 | " |
| 7 | Al 6063 | C300 | D3 (modified) | 2.00 | 600 | Good | 66 | 59 | " |
| 6 | Al 7075 | C300 | D3 (modified) | 1.80 | 750 | Good | 77 | 72 | " |
| 5 | Al 7075 | C300 | D2 (modified) | 2.25 | 750 | Good | 69 | 57 | " |

Notes: (a) Die D1 = flat-face die for rectangular shape
D2 = curved die for round shape
D3 = streamlined die for rectangular shape

(b) In all extrusions, the container temperature was 500 F.

(1) The main objective of evaluating the capabilities of CAD/CAM techniques was completely achieved by measuring the extrusion load, the metal flow, and the dimensions of the streamlined die, manufactured by CAM method.

(2) The lubrication breakdown problem was caused by the unconventional die design and die-container arrangement used in these preliminary extrusions. The problem may be totally eliminated by using a conventional hydrostatic or cold extrusion tooling arrangement, used in other extrusion studies, conducted at Battelle.

In extruding copper, the grid lines marked on the surface of the billet were quite visible on the butt. These grid lines were used to determine the metal flow along the die surface.

## Evaluation of Results

### Metal Flow

The surface of a streamlined die for lubricated extrusion is determined by the geometrical construction illustrated in Figure 3-2. The following assumptions are made in deriving the die surface:

(1) The billet undergoes deformation with minimum amount of work expended for redundant deformation and friction. This requires that the friction at the billet-container and billet-die interfaces should be minimum. Thus, the error introduced by this assumption would depend on the values of friction factor considered at the sliding surfaces.

(2) The metal flow is such that there is a neutral axis perpendicular to the cross-sectional plane at the die entrance. This is strictly true only for axisymmetric extrusion. In extrusion of shapes, there is probably a complex neutral surface instead of a neutral axis. This assumption was made to simplify the analysis as the neutral surface cannot be determined without constructing

the die surface first. It is obvious that the error introduced would depend on the extent by which the product shape deviates from the round shape.

(3) The flow lines along the die surface are such that their projection on a cross-section plane, say at die entrance, are straight-lines (Figure 3-2).

The metal flow along the die surface and the die configuration are completely defined by the analysis based on the above assumptions.

To compare the metal flow predicted theoretically with the actual metal flow, gridlines, approximately 0.5-inch apart and 0.010-inch deep, were marked on the surface of the copper billet No. 12. The conditions under which the billet was extruded are given in Table 3-4. The billet was only partially extruded. The shape of the marked lines on the butt represented the path followed by the material points during steady-state extrusion.

Figure 3-13 shows the experimental flow lines and the flow lines predicted theoretically. The theoretical flow lines are quite close to the actual flow lines near the planes of symmetry, namely xx' and yy'. Away from the planes of symmetry, the difference is quite appreciable. Also, the deviation increases towards the die exit. This difference can be explained as follows. The theoretical flow lines are determined with the assumption that the friction is negligible. However, in the actual experiment, the friction was quite high because of the shearing of the material at the die lip as explained earlier. High friction introduces redundant deformation which influences the path followed by the material points. Also, the product shape is very wide and thin, and near the die exit, the metal flow is not axisymmetric. Some difference between the theoretical and the experimental flow lines is, therefore, introduced by the assumption of a single neutral axis, instead of a neutral surface.

It is interesting to note that the flow lines observed in present experiments with copper resemble those obtained by Sukolski[11] in extrusion of model material (plasticine) through a flat-face die. (See Figure A-1, Appendix A). Also, the experimental flow lines when projected on an axial plane are perpendicular to initial billet boundary and the final extrusion shape. Perlin[12] and Sukolski[11] have made similar observations on metal flow in extrusion of shapes. The straight-line approximation made in the die-design procedure for the flow lines along the die surface is, however, quite close to the curved line pattern observed experimentally, Figure 3-13.

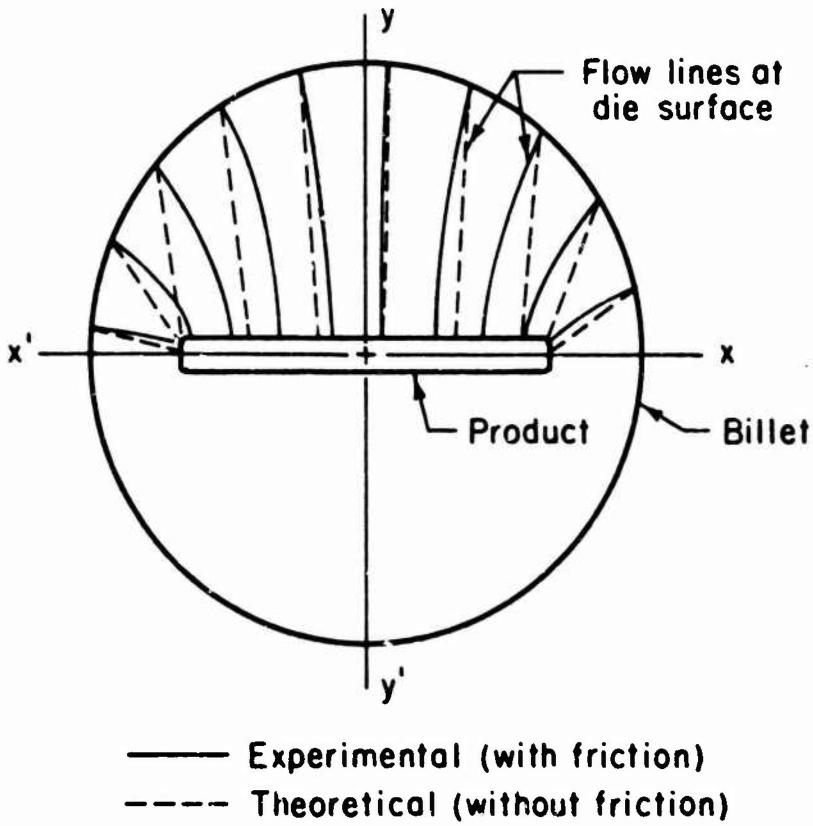



FIGURE 3-13. COMPARISON OF ACTUAL METAL FLOW WITH THAT PREDICTED FROM THEORETICAL MODEL (BCL EXTRUSION NO. 12, TABLE 3-4)

## Extrusion Pressure

As mentioned earlier, "SHAPE", the system of computer program developed in this project, includes a theoretical analysis for predicting the pressure required to extrude a shape. In the analysis, the extrusion pressure is determined as a function of flow stress of the material, frictional conditions at the sliding surfaces and process conditions, such as ram speed, billet temperature, dimensions of billet and the extruded shape, and die configuration. Thus, to predict the extrusion pressure under given process conditions, information on flow stress of the material and on friction factors for the sliding surfaces is needed. Existing data on flow stress of materials is very limited. Reference 15 gives the flow-stress data for some materials. The friction factors for container-material and die-material interfaces depend upon some of the process conditions, such as nature of lubrication, temperatures of the contacting surfaces, and the surface finish of the tooling, etc. A special test must be designed and conducted to obtain accurate values of friction factors.

To obtain data on flow stress of the materials, extruded in this study, the ideal procedure would have been to conduct isothermal compression or torsion tests with specimens made from billet stock. However, due to the limited scope of the trials, separate-isothermal compression tests were not conducted. Instead, existing flow stress data from Reference 15 were used. Since the data on Al 6063 was not available, the flow stress of Al 1100, which is quite similar to Al 6063, was used.

In the first set of extrusion trials, the extrusions through the dies were virtually without lubrication because of severe die galling. Therefore, the following values of friction factors were assumed for the first set of trials:

- Friction factor at die-material interface, $m_d = 1.0$
- Friction factor at container-material interface, $m_c = 0.15$.

With these friction factors, the maximum extrusion pressures were calculated using "SHAPE". The predicted and the experimental values of extrusion pressures are given in Table 3-2. Comparison between the experimental and predicted extrusion pressures is fair. The predicted pressures are always higher than the experimental values and the maximum difference is about 23 percent. Lack of proper information on friction conditions at the sliding surfaces and on flow stress data seem to be the probable reasons for the difference.

TABLE 3-5. COMPARISON OF PREDICTED AND MEASURED EXTRUSION PRESSURES FOR THE FIRST SET OF TRIALS

Area Reduction = 19.2, $m_c$ = 0.15

| Billet No.[a] | Material | Die | Product Shape | Maximum Extrusion Pressure (ksi) Measured | Predicted ($m_d$) |
|---|---|---|---|---|---|
| 8 | Al 6063 | Curved,D2 | Round | 53 | 59 (1.0) |
| 3 | Al 7075 | Streamlined,D3 | Rectangle | 89 | 112 (1.0) |
| 9 | Al 6063 | Streamlined,D3 | Rectangle | 59 | 62.5 (1.0) |
| 10 | Al 6063 | Flat Faced,D1 | Rectangle | 54 | 62.3 (1.0) |
| 1 | Al 7075 | Flat Faced,D1 | Rectangle | 86 | 110 (1.0) |

(a) See Tables 3-3 and 3-4.

TABLE 3-6. COMPARISON OF PREDICTED AND MEASURED EXTRUSION PRESSURES FOR SECOND SET OF TRIALS

Area Reduction = 19.2, $m_c$ = 0.15

| Billet No.[a] | Material | Die | Product Shape | Maximum Extrusion Pressure (ksi) Measured | Predicted ($m_d$) |
|---|---|---|---|---|---|
| 13 | Cu 110 | Flat Face,D1 | Rectangle | 85 | 92.6 (1.0) |
| 12 | Cu 110 | Modified Streamlined,D3 | Rectangle | 78 | 66 (0.5) |
| 11 | Al 6063 | Modified Curved, D2 | Round | 54 | 63.7 (0.5) |
| 7 | Al 6063 | Modified Streamlined,D3 | Rectangle | 66 | 70.2 (0.5) |
| 6 | Al 7075 | Modified Streamlined,D3 | Rectangle | 77 | 88.4 (0.5) |
| 5 | Al 7075 | Modified Curved, D2 | Round | 69 | 81.5 (0.5) |

(a) See Tables 3-3 and 3-4.

As mentioned earlier, after the first set of trials, the streamlined die, D3, and the curved die, D2, were modified to improve lubrication. However, partial lubrication was only achieved due to the shearing of a thin foil by the die lip. Friction factor $m_d$ was assumed to be 0.5 and $m_c$ was taken to be 0.15 in calculating the pressures. The predicted pressures are given in Table 3-6. Again, the predicted pressures are quite close to the actual pressures, the maximum difference being 18 percent. The difference is attributed, as before, to inadequate information on flow-stress data and on frictional conditions at the die-material interface.

It is interesting to look at the effect of product shape on extrusion pressure. Comparing extrusion pressures for billet numbers 11 and 7, the effect of change of shape from a round to a thin rectangle is to increase the pressure by 22 percent. With billets numbers 6 and 5, the increase in pressure is about 12 percent. Qualitatively, this trend agrees with the theoretical results, obtained earlier in studying the extrusion of a modular elliptic shape, Chapter 2, and with earlier work.[16] The increase in pressure with change of extrusion shape can be explained as follows: The deformation is axisymmetric when a circular shape is extruded from a cylindrical billet. However, when the product shape is noncircular, additional redundant work is expended to deform the material to the nonaxisymmetric shape. Also, the calculated surface area of the streamlined die for extruding the rectangular shape is larger than the surface area of the die for extruding the round shape. This increases the energy dissipated in overcoming friction. The total effect is to increase the total extrusion pressure.

## Conclusions

From the results of the extrusion trials, the following conclusions are drawn:

(a) The desired streamlined surface was machined on the EDM electrode with NC tape prepared from SHAPE, the system of computer programs developed in this project. The NC programs, therefore, are found to be correct and adequate for simple shapes like a round-cornered rectangle.

(b) The extrusion pressures predicted by SHAPE agreed reasonably well with the experimental values. The maximum difference was about 23 percent. The simplified theory developed in this program seems to be sufficiently accurate for predicting extrusion loads for practical purposes.

(c) The comparison between the actual metal flow along the die surface, obtained from extrusion trials, and the assumed direction of flow in the die design was only fair. High-frictional conditions at the material die interface were partly responsible for the difference.

(d) Proper billet lubrication is very important in shape extrusion. Due to the high area reductions and the non-axisymmetric nature of the deformation, portions of the billet surface are stretched to a high degree. The lubricant film must be capable of stretching with the surface. Also, the die design from the point of view of lubrication is very important. The billet surface must be deformed smoothly without causing lubrication breakdown.

## SUMMARY

This chapter describes the work conducted towards applying CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) to extrusion of simple structural shapes. Even for simple shapes like T's and L's, the surface of a streamlined die cannot be defined analytically. No consistent technique has been developed to define and manufacture complex surfaces of a streamlined die. In this work, a numerical method of determining the shape of a streamline die in lubricated extrusion is presented.

A simplified, uniform energy method is developed to calculate the extrusion load and its components due to internal deformation, shear deformation, and friction. Die-pressure distribution along the die surface is also calculated. Information on load and pressure distribution should help in optimizing the extrusion process, and in proper selection of the extrusion

press as well as in proper design of tooling.

The streamlined die surface is too complex to be machined easily by conventional techniques like copy turning or milling. Therefore, special-purpose computer programs are written to generate the die surface by NC (Numerical Control) machining. The programs can be used to machine an EDM (Electro-Discharge Machining) electrode for manufacturing the dies by EDM process, or a master pattern can be machined which may be used to cast the dies.

The computer programs to define the surface of a streamlined die, to calculate the load and die-pressure distribution, and to generate coordinate data for machining of the streamlined die are put together in a system of programs called "SHAPE". SHAPE can be used in batch, as well as in interactive mode. In the interactive mode, the designer can interact with the program to select the shape and the length of the die, and to obtain information on load and pressure calculation as well as to select the proper size cutter for NC machining of the dies.

Extrusion trials were conducted to demonstrate the CAD/CAM techniques developed in the program. A round-cornered rectangle and a circular shape were extruded from copper 110, Al 6063, and Al 7075, under lubricated and nonlubricated conditions. For lubricated extrusion of the rectangular shape, a streamlined die was designed and fabricated with the help of the developed software package, SHAPE. A flat-faced die was made for nonlubricated extrusion of the rectangular shape. Round shapes were extruded with a curved die to evaluate the effect of shape on extrusion pressure and metal flow. The results showed that the desired optimal die shape was machined with the NC programs. The agreement between measured values and theoretical predictions concerning metal flow and extrusion loads was quite good. Thus, the results have demonstrated the applicability and accuracy of the CAD/CAM techniques developed in the present program.

## REFERENCES


(1) Akeret, R., "Unconventional High-Speed Extrusion Processes for the Harder Aluminum Alloys", (in German), Z. Metallkunde, 64, 1973, pp 311-319.

(2) Lahoti, G. D., and Altan, T., "Prediction of Temperature Distributions in Tube Extrusion Using a Velocity Field Without Discontinuities", Proceedings of the Second North American Metalworking Research Conference, Madison, Wisconsin, May 20-22, 1974, pp 209-224.

(3) Seeds, W. E., "Preform Design for Gas Turbine Blades", Engineering Materials and Design, November, 1973, pp 27-31.

(4) Hill, R., The Mathematical Theory of Plasticity, Oxford at the Clarendon Press, 1950.

(5) Chen, P. C. T., and Ling, F. F., "Upper-Bound Solutions to Axisymmetric Extrusion Problems", International Journal of Mechanical Sciences, Vol. 10, 1968, p 863.

(6) Siebel, E., "Fundamentals and Concepts of Forming", (in German), Werkstattstechnik und Maschinenbau, 40, 1950, p 373.

(7) Kamyab, S., and Alexander, J. M., "Pressure Distribution in Hydrostatic Extrusion Dies", Journal of Strain Analysis, Vol. 17, No. 3, 1972, p 205.

(8) Doble, G. S., "Manufacturing Technology for the Extrusion of Superalloy Structural Shapes", Technical Report AFML-TR-68-325, October, 1968.

(9) Lahoti, G. D., and Altan, T., "Optimum Die Profile for Drawing of Shells and Cups", Proceedings of Third North American Metalworking Research Conference, Carnegie Press, Carnegie-Mellon University, Pittsburgh, Pennsylvania, May, 1975.

(10) Nagpal, V., and Altan, T., "Analysis of the Three-Dimensional Metal Flow in Extrusion of Shapes with the Use of Dual Stream Functions", Proceedings of Third North American Metalworking Research Conference, Carnegie Press, Carnegie-Mellon University, Pittsburgh, Pennsylvania, May, 1975.

(11) Annual Report to the Extrusion Committee for 1956 by P. J. Sukolski, The British Iron and Steel Research Association Report MW/G/83/56.

(12) Perlin, I. L., "Theory of Metal Extrusion", Published by Metallurgiya, Moscow, 1964, Foreign Translation No. FTD-HT-23-616-67, June, 1968.

(13) Dorn, W. S., and McCracken, D. D., Numerical Methods with FORTRAN IV Case Studies, John Wiley and Sons, New York, 1972.

(14) Perlmutter, I., DePierre, V., and Pierce, C. M., "Lubrication as a Parameter in the Extrusion of Metals", Friction and Lubrication in Metal Processing, ASME, 1966, pp 147-161.

(15) Douglas, J. R., and Altan, T., "A Study of Mechanics of Closed-Die Forging - Phase II", Final Report, Contract DAAG46-71-C-0095, Battelle's Columbus Laboratories, Columbus, Ohio, November, 1972.

(16) Abson, D. J., and Gurney, F. J., "Investigation of Parameters Involved in Metal Processing Operation", Technical Report AFML-TR-73-281, December, 1973.

APPENDIX A

# DETERMINATION OF THE DIE GEOMETRY

## APPENDIX A

## DETERMINATION OF THE DIE GEOMETRY

In shape extrusion, the die must provide a smooth transition from the circular billet to the final extrusion shape. In addition, the die surface must be such that the material undergoes minimum redundant deformation and exits from the die with a uniform velocity. The shape of the die surface affects the metal flow. To obtain an optimal die design, the usual procedure is to analyze the characteristics of metal flow through dies of different configurations and to select the die configuration which provides the desired metal flow. As a first step of this procedure, the die shape must be defined analytically or numerically.

Any definition of the die surface must fulfill two requirements. First, the definition should be as general as possible so that in the optimization process maximum possible die configurations are compared. Second, the definition should allow modifications in a portion of the die surface without affecting the remaining surface. This would make simpler the process of modifying a die profile based on experimental studies. Die surface modifications may be desired to obtain more uniform metal flow or to relieve stress concentrations at particular locations in the die.

In extrusion of round bars or elliptic shapes, it is possible to define the die surface analytically. For nonsymmetric shapes, like T, L, U and others, it is rather difficult to describe analytically the complex die surface which provides a smooth transition from a round cross section to these extruded shapes. Consequently, a numerical procedure is used to describe the die surface. This procedure is based on simplified principles of theory of plasticity, and previous analytical and experimental studies conducted on shape extrusion.

## Theoretical Considerations

In order that no twisting or bending of the material occurs as it emerges from the extrusion die, the necessary condition on metal flow is that the exit velocity must be uniform across the cross section. This velocity, $V_f$, is given by:

$$V_f = V_o \frac{A_o}{A_f} \quad , \qquad \text{(A-1)}$$

where $V_o$ = initial velocity

$A_o$ = initial area of billet

$A_f$ = final area of extrus n.

To have a uniform velocity at the exit, all the elemental (small) portions of the initial cross section must undergo equal reductions. Thus, the die must be designed such that it allows an equal reduction for all the elements of the initial cross section.

## Numerical Procedure

Assuming that the suggested die geometry provides a uniform velocity distribution at the exit, we shall construct numerically the geometry of such a die by performing the following steps:

(a) Determination of the Neutral Axis

(b) Determination of the Material Path Lines on the Die Surface

(c) Description of a General Die Surface.

## Determination of the Neutral Axis

The purpose of defining a neutral axis is that the initial and the final cross sections would be divided into elemental areas, starting from the neutral axis. The neutral axis is defined here as curved line perpendicular to which the metal flow is zero. According to this definition, in extrusion of rods, the extrusion axis is the neutral axis. In shape extrusion, however, the neutral axis may not coincide with the extrusion, or the billet axis.

The following conditions are used to determine the neutral axis:

(1) The neutral axis lies on planes of symmetry. Thus, for extruded shapes, such as round, rectangle, H, I, and hexagonal, which have two or more planes of symmetry, the neutral axis coincides with the extrusion axis, provided these shapes are not placed at an offset from the billet axis. Figure 3-2 shows an example of such a case. For shapes like T, U, Z which have one plane of symmetry, the neutral axis lies on this plane, but its exact location along this plane has to be determined from some additional requirements.

(2) The volume elements of the initial billet must be deformed with as little redundant work as possible. Consequently, shear strains should be minimized. For shapes like T, this can be done by locating the neutral axis along the plane of symmetry such that an additional material path line lies exactly on the radial plane drawn from the neutral axis. Thus, by this procedure, we are creating another plane of symmetry, which would tend to reduce the shear strains near it. Figure 3-3(a) shows an example of one such case. The location of the neutral axis 00' on plane xx' is determined such that the radial plane $x = x_c$ coincides with the material flow line b-2. The necessary condition, of course, is that the ratio of the areas bounded by planes $y = 0$, $x = x_c$ and the entrance boundary $B_o$ (billet shape) to that bounded by planes $y = 0$, $x = x_c$ and exit boundary $B_f$ (extrusion shape) is equal to the overall area reduction $(A_o/A_f)$. $A_o$ is the initial cross-sectional area of the billet and $A_f$ is the final cross-sectional area of the product. It may be pointed out here that this procedure of determining neutral axis also divides the deformation zone into quadrants, such that the area reduction in each quadrant is the same. This is similar to the rule of thumb used by experienced die designers in placing the extruded shape opening with respect to the billet axis.[8] For shapes which do not have any plane of symmetry, the neutral axis is located by the intersection of two planes $x = x_c$ and $y = y_c$, as shown in Figure 3-3b.

## Determination of Material Path Lines Along the Die Surface

To determine the material path lines along the die surface, the movement of the elements of the initial cross section, which are on the billet boundary, must be predicted. Since it is assumed that the material exits from the die with a uniform velocity, each initial elemental area undergoes the same area reduction. Consequently, we know what final areas the boundary elements will have at the die exit. However, we do not know where a particular element of the initial billet boundary will end up at the die exit. Therefore, we assume that a radial line drawn from the neutral axis on the initial cross section shows up as a radial line drawn from the neutral axis on the exit cross section. This assumption implies that, as shown in Figure 3-2, line 0-2 would end up as line 0'-2' at the die exit. Also, the ratio of the area 012 to the area 0'1'2' equals $(A_o/A_f)$. Thus, a material point moves from 2 to 2' as the extrusion proceeds. By this procedure, the end points of the material path lines at the die exit are determined. The same construction can be used to obtain the end points of the material paths for shapes having one, or no plane of symmetry (Figure 3-3). It may, however, be pointed out that this procedure would fail for shapes like U and H. These shapes have re-entrant angles and a radial line from the neutral axis intersects the boundary of the final shape at more than one point. Some T's also fall in this category. This limitation of the procedure has not been overcome yet and will be dealt with in the future.

The above procedure gives the end positions of the material path lines, at entrance and exit, on the die surface, but the actual paths between the end points are not obtained. The paths followed by the material points in the deformation zone depend on the process variables including the shape of the die. Consequently, the die shape must be defined first.

## Description of a General Die Surface

To obtain a general and arbitrarily defined die surface, which provides a smooth transition from the initial circular billet to the final extrusion shape, curves are fitted between end points of the material path lines

at the die entrance and exit. Thus, numerically, a general three-dimensional die surface is described. Different die surfaces can be obtained by changing the curves fitted between the end points. Also, any portion of the die surface can be modified without affecting the remaining surface by changing the curves fitted in that portion.

The choice of the curves fitted between the boundaries of the deformation zone is based on theoretical considerations, previous experience, and intuition. In extrusion of axisymmetric shapes like rods or tubes, previous studies at Battelle[9] have shown that a polynomial curve gives the optimal die shape. For axisymmetric shapes, this curve lies on a radial plane, i.e., a plane which contains the billet axis. However, for a nonsymmetric shape, theoretical and experimental studies[10,11] have shown that the flow lines do not lie on a radial plane. In extrusion through flat-faced dies, Sukolski[11] observed from his model experiments that the flow lines, when projected on an axial plane, (i.e., a plane perpendicular to the billet axis), were perpendicular to the initial billet boundary and the final extrusion shape, as shown in Figure A-1. Similar observation on the pattern of metal flow in shape extrusion has also been made by Perlin[12] for nonlubricated extrusion through flat-faced dies. In lubricated extrusion process, the flow pattern derived theoretically in our earlier work on extrusion of an elliptical shape from a cylindrical billet also exhibits this characteristic. However, this flow pattern is for a simple modular shape of an ellipse which does not have any sharp corners or re-entrant angles. For more complex structural shapes like U and H, it is not possible to predict whether the flow lines in the die would still be perpendicular to the initial and final shapes or not. Model studies and trials to be conducted later in this project are expected to provide some information on this point.

In view of the above observations made in this study, it was decided to use a simplified procedure for describing the die surface. It was assumed that the curves representing the flow lines lie on a plane containing the billet axis, as seen in Figure 3-4. Also, the curves themselves have a polynomial form which have been shown to be the optimal shape for rod or tube extrusion. Appendix D gives the mathematical details of this construction.

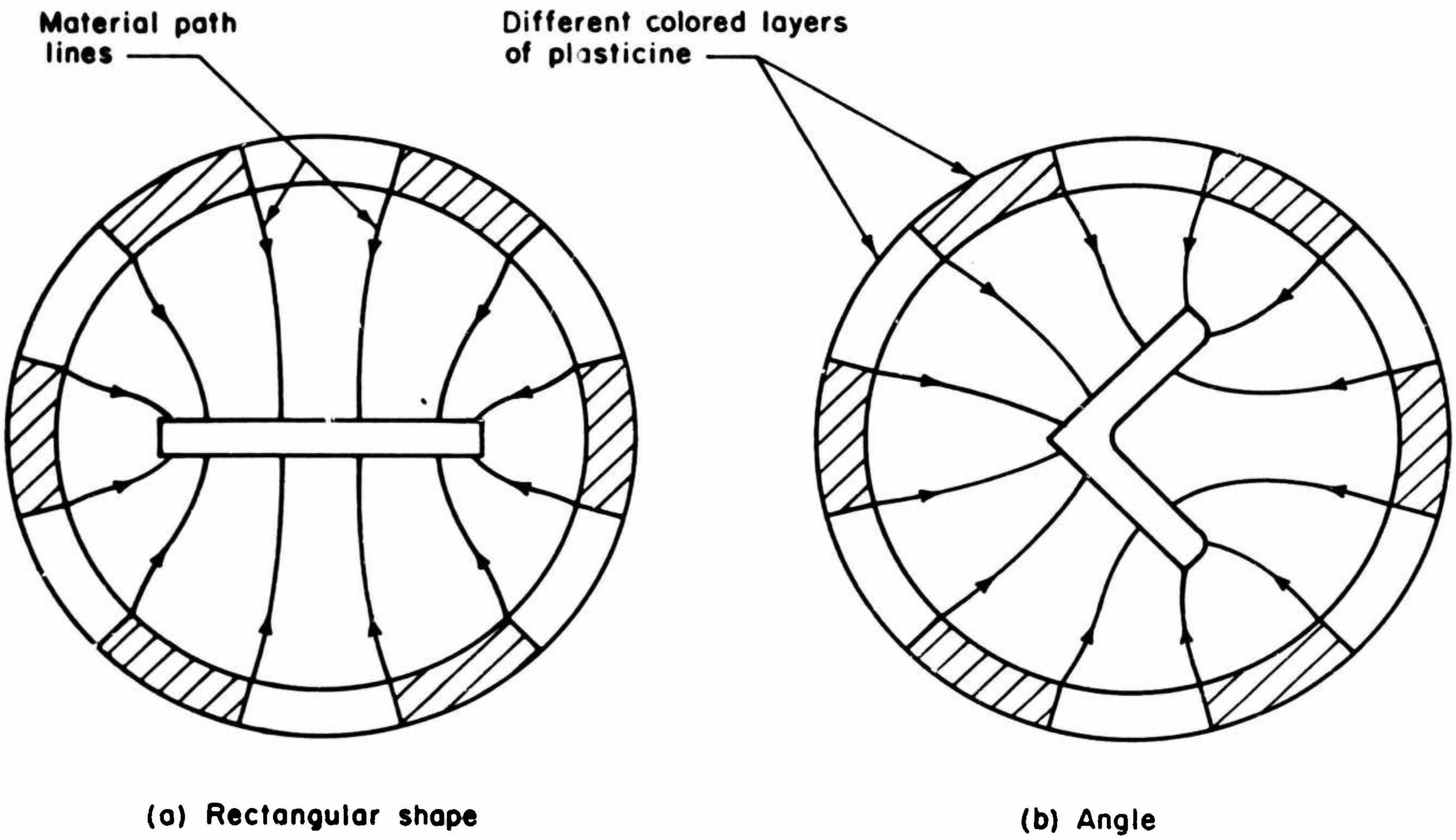



FIGURE A-1. DIAGRAMMATIC CROSS SECTIONS OF PRODUCT AND SPECIMEN SHOWING RADIAL PROJECTION OF DIRECTIONS OF FLOW OF POINTS ON ORIGINAL SURFACE

(The Die had a Flat Face, 1/16" Inlet Radius and 1/16" Throat Depth all Round. Material was plasticine).(11)

# APPENDIX B

## CALCULATION OF EXTRUSION LOAD AND DIE PRESSURE DISTRIBUTION

## APPENDIX B

### CALCULATION OF EXTRUSION LOAD AND DIE PRESSURE DISTRIBUTION

Siebel's method[6] has been extensively used to analyze plane strain as well as axisymmetric metal-forming problems. Here, this method is extended to analyze the three-dimensional problem of shape extrusion. The following assumptions are made:

(1) Plane sections perpendicular to the extrusion axis remain plane.

(2) The plastic deformation zone is bounded by cross-sectional planes at entrance and exit of the die.

(3) The effective strains, effective strain rates and the flow stress of the deforming material is assumed to vary only in axial direction (direction of extrusion).

(4) In calculating the effective strains and strain rates, the redundant shear strains and strain rates are neglected. In calculating flow stress, this assumption would introduce only insignificant error since for hot extrusion, flow stress is a weak function of strain rate for most materials. In the calculation of rate of energy dissipation due to plastic deformation, this assumption would introduce an error which previous experience[9,10] has shown to be small at least for plane and axisymmetric problems.

(5) Maximum extrusion pressure occurs at the very beginning of the steady-state extrusion process when the material just starts to exit from the die.

(6) Friction is taken into account by assuming that the friction shear stress ($\tau$) is directly proportional to the flow stress ($\bar{\sigma}$) of the material, i.e.,

$$\tau = \frac{m}{\sqrt{3}} \bar{\sigma} \quad .$$

m is a constant of proportionality and is called friction shear factor.

## Theoretical Analysis

The total rate of energy supplied ($\dot{E}_t$) at any instance must be equal to the sum of the rates of energy dissipated during the extrusion process. This is expressed by the Equation:

$$\dot{E}_t = \dot{E}_{fc} + \dot{E}_i + \dot{E}_{sh} + \dot{E}_{fd} + \dot{E}_{f\ell} . \quad \text{(B-1)}$$

The symbols used are explained in the Nomenclature at the end of this Appendix. The various terms of Equation (B-1) are determined as follows:

### Rate of Energy Supplied ($\dot{E}_t$)

The rate of energy supplied is given by:

$$\dot{E}_t = P_t V_o = \frac{\Pi}{4} D_o^2 P_{avg} V_o . \quad \text{(B-2)}$$

$P_t$ is the total extrusion load and $P_{avg}$ is the mean pressure required to extrude the material.

### Rate of Energy Dissipated Due to Container Friction ($\dot{E}_{fc}$)

The rate of energy lost due to friction at the container wall is given by:

$$\dot{E}_{fc} = \Pi D_o L_c \tau_c V_o = \frac{\Pi}{4} D_o^2 P_{fc} V_o . \quad \text{(B-3)}$$

$\tau_c$ is the shear stress due to friction at the material-container interface and is given by relation:

$$\tau_c = m_c \frac{\bar{\sigma}}{\sqrt{3}} . \quad \text{(B-4)}$$

From Equation (B-3), the component of extrusion pressure due to friction ($P_{fc}$) is:

$$P_{fc} = \frac{4L_c}{D_o} \left( m_c \frac{\bar{\sigma}}{\sqrt{3}} \right) . \quad \text{(B-5)}$$

In the analysis, the flow stress $\bar{\sigma}$ is taken to be a function of strain, strain rate and temperature. Since the billet in the container is not plastically deforming, the flow stress $\bar{\sigma}$ in expression (B-5) corresponds to the yield stress ($\bar{\sigma}_y$) of the incoming material at the billet temperature.

As extrusion proceeds, the length of the billet in contact with the container ($L_c$) decreases. $L_c$, which corresponds to the maximum extrusion pressure, is given by:

$$L_c = L_o - \frac{1}{A_o}(V_L + A_f l_d) \quad . \tag{B-6}$$

Rate of Energy Dissipated Due to Internal Deformation ($\dot{E}_i$)

$$\dot{E}_i = \dot{E}_{ideal} + \dot{E}_{red} \, ,$$

where $\dot{E}_{ideal}$ = ideal rate of energy dissipation needed for the reduction in cross-sectional area and shape

$\dot{E}_{red}$ = redundant rate of energy dissipated in causing the change in cross section and shape.

$\dot{E}_{ideal}$ for a work-hardening material is given by:

$$\dot{E}_{ideal} = A_o V_o \int_{\dot{\bar{\varepsilon}}} \bar{\sigma} \, d\dot{\bar{\varepsilon}} = A_o V_o P_{id} \quad . \tag{B-7}$$

The expression (B-7) is evaluated numerically. The deformation zone is divided into a number of slabs. The flow stress in any slab is determined corresponding to the total effective strain and strain rate in that slab.

For axisymmetric deformation, the effective strain, $\bar{\varepsilon}$, at any cross section of area A of the deformation zone is given by:

$$\bar{\varepsilon} = \ln (A_0/A) \quad , \tag{B-8}$$

whereas for plane-strain deformation

$$\bar{\varepsilon} = 2/\sqrt{3} \, \ln (A_o/A) \quad . \tag{B-9}$$

Since initially the billet is cylindrical, the deformation in the beginning of the deformation zone corresponds to the axisymmetric case. Therefore, Equation (B-8) is used in calculating the total effective strain. By definition, the effective strain rate $\dot{\bar{\varepsilon}}$ is:

$$\dot{\bar{\varepsilon}} = \frac{d\bar{\varepsilon}}{dt} \quad .$$

In case the plane sections remain plane, the strain rate in finite difference form is given by:

$$\dot{\bar{\varepsilon}} = \frac{\Delta\bar{\varepsilon}}{\Delta z} \cdot V_z \quad , \tag{B-10}$$

where $V_z$ = axial velocity

$\Delta z$ = small distance over which the difference in strain, $\Delta\bar{\varepsilon}$, is measured.

The flow stress at any section is determined from the flow stress data corresponding to the strain rate and strain calculated from Equations (B-8) and (B-10). The shear strains are not included in Equations (B-8) and (B-10), which are really the expressions based on ideal deformation.

The component $\dot{E}_{red}$ cannot be determined without the knowledge of strain-rate distribution in the plastic zone. The study on the modular elliptic shape, however, indicated that the contribution of the component $\dot{E}_{red}$ to extrusion load is small in relation to the other components. Thus, at the present time, $\dot{E}_{red}$ is neglected in calculating extrusion load and die pressure distribution.

Rate of Energy Dissipation Due to Tangential Velocity Discontinuities ($\dot{E}_{sh}$)

The concept of having a tangential velocity discontinuity in the deformation of a work-hardening material is not rigorously correct. However, the effect of having a sharp change in tangential velocity of deformation over a small distance in the deformation zone can be approximated by assuming a velocity discontinuity. If the die surface is such that the material has to bend at the die entrance, or exit, certain amount of the rate of energy is dissipated due to shear deformation. For axisymmetric extrusion through a conical die, $\dot{E}_{sh}$ is given by:[6]

$$\dot{E}_{sh} = \frac{\Pi}{4} D_o^{\,2} V_o \left( \frac{\bar{\sigma}_o}{\sqrt{3}} \frac{2\alpha}{3} + \frac{\bar{\sigma}_e}{\sqrt{3}} \frac{2\alpha}{3} \right) = \frac{\Pi}{4} D_o^{\,2} V_o P_{sh} , \qquad \text{(B-11)}$$

where $\bar{\sigma}_{\alpha}$ = half of the included angle of the conical die.

$\bar{\sigma}_o$ = flow stress of material at entrance to the die.

$\bar{\sigma}_e$ = flow stress of material at die exit.

In extrusion of nonsymmetric shapes, $\dot{E}_{sh}$ is calculated using the same expression (B-11) with the difference that the angle $\alpha$ is now taken to be the mean of the angles that the die periphery makes with the extrusion axis at the entrance ($\alpha_o$) and at the exit ($\alpha_e$).

Thus, for nonsymmetric deformation:

$$\dot{E}_{sh} = \frac{\Pi}{4} D_o^{\,2} V_o \left( \frac{\bar{\sigma}_o}{\sqrt{3}} \frac{2}{3}|\alpha_o| + \frac{\bar{\sigma}_e}{\sqrt{3}} \frac{2}{3}|\alpha_e| \right) = \frac{\Pi}{4} D_o^{\,2} V_o P_{sh} . \qquad \text{(B-12)}$$

<u>Rate of Energy Dissipation</u>
<u>Due to Die Friction ($\dot{E}_{fd}$)</u>

$\dot{E}_{fd}$ is given by:

$$\dot{E}_{fd} = \int_{A_d} \tau_d |\Delta v| dA_d = \Pi/4 \; D_o^{\,2} V_o P_{fd} . \qquad \text{(B-13)}$$

$\tau_d$ is the friction shear stress at the material-die interface and is given by:

$$\tau_d = m_d \frac{\bar{\sigma}}{\sqrt{3}} .$$

The relative velocity $\Delta v$ is equal to the tangential velocity of the material at the die surface. Assuming that plane sections remain plane, the tangential velocity $V_t$ of the material at any point on the interface is given by:

$$V_t = V_z \cdot \frac{\Delta \ell}{\Delta z} ,$$

where $V_z$ is the axial velocity and $\Delta \ell$ is the length of the material path line between a small axial distance $\Delta z$. Substituting for $\tau_d$ and $\Delta v$ in Equation (B-13), an expression for $\dot{E}_{fd}$ is obtained which can be evaluated numerically.

Rate of Energy Dissipated Due to Friction at the Die Land ($\dot{E}_{f\ell}$)

Using a relation similar to (B-13), $\dot{E}_{f\ell}$ can be expressed by:

$$\dot{E}_{f\ell} = V_o \left( m_d \frac{\bar{\sigma}_e}{\sqrt{3}} \right) L_d \, C = A_o \, V_o \, P_{f\ell} \quad , \qquad \text{(B-14)}$$

where $C$ = perimeter of the extruded shape

$L_d$ = length of the die land.

Total Rate of Energy Dissipation

Substituting for various terms in (B-1), an expression for $\dot{E}_t$ is obtained which can be evaluated numerically. Similarly, the total extrusion pressure $P_{avg}$ can be obtained from the sum of its components:

$$P_{avg} = P_{fc} + P_{id} + P_{sh} + P_{fd} + P_{f\ell} \quad . \qquad \text{(B-15)}$$

The total extrusion load is given by:

$$\text{Extrusion Load} = \frac{\Pi}{4} D_o^{\,2} \, P_{avg} \quad . \qquad \text{(B-16)}$$

## Die-Pressure Distribution

In calculating the die-pressure distribution, it is assumed that the principle stresses in the deformation zone vary only along the axial direction. The mean axial compressive stress, $\sigma_z$, acting on any cross section of the material in the deformation zone can be approximated by the extrusion pressure, $P_a$, needed to extrude the material up to that cross section. Distribution of $P_a$ and thus $\sigma_z$ can be calculated using Equation (B-15). The condition that the material in the deformation zone is undergoing plastic deformation requires:

$$P - \sigma_z = \bar{\sigma} \quad ,$$

$$\text{or} \quad P = \bar{\sigma} + \sigma_z \quad . \qquad \text{(B-17)}$$

P is the mean-normal pressure acting on the die surface at any cross section. Die pressure P can be calculated using Equation (B-17).

## Nomenclature

$A_d$ = Surface area of the die

$A_f$ = Final area of the extrusion (product)

$D_o$ = Diameter of the billet

$\dot{E}_{fc}$ = Rate of energy dissipated due to friction at the container wall

$\dot{E}_{fd}$ = Rate of energy dissipated due to friction at the die surface

$\dot{E}_{f\ell}$ = Rate of energy dissipated due to friction at the die land

$\dot{E}_i$ = Rate of energy dissipated due to plastic deformation

$\dot{E}_{sh}$ = Rate of energy dissipated due to shearing caused by tangential velocity discontinuities

$\dot{E}_t$ = Total rate of energy supplied

$L_c$ = Length of the billet in contact with the container

$L_o$ = Initial length of the billet

$l_d$ = Length of the die land

$m_c$ = Friction shear factor for the container-material interface

$m_d$ = Friction shear factor for the die-material interface

$P_{avg}$ = Mean extrusion pressure

$P_{fc}$ = Component of extrusion pressure due to friction at the container wall

$P_{fd}$ = Component of extrusion pressure due to die friction

$P_{f\ell}$ = Component of extrusion pressure due to die-land friction

$P_{id}$ = Component of extrusion pressure due to internal deformation

$P_{sh}$ = Component of extrusion pressure due to shear deformations at die entrance and exit

$P_t$ = Total extrusion load

$V$ = Volume of plastic zone

$V_o$ = Speed of the ram

$V_L$ = Volume of the material in the die (volume of the die cavity)

$\Delta v$ = Tangential velocity discontinuity

$\alpha_o, \alpha_e$ = Average angles that the die surface makes with the extrusion axis at the die entrance and exit, respectively

$\bar{\sigma}$ = Flow Stress

$\bar{\varepsilon}$ = Effective strain

$\dot{\bar{\varepsilon}}$ = Effective strain rate

# APPENDIX C

## NUMERICAL CONTROL (NC) MACHINING OF THE EDM ELECTRODE

APPENDIX C

## NUMERICAL CONTROL (NC) MACHINING OF THE EDM ELECTRODE

This appendix presents the mathematical basis used in calculating positions of the ball-end milling cutter used for NC machining of the electrode. The calculation of the cutter paths is done numerically by special FORTRAN based computer programs developed for this purpose. The system of programs called SHAPE includes these programs.

To generate a surface by a rotating spherical tool, the tool must machine the surface in a predetermined fashion. In the present case, the ball-end mill cutter is moved along the material path lines on the die surface, as shown in Figure C-1.

To generate the surface of the EDM electrode, the tool position should be such that the spherical cutting portion of the tool is always normal to the surface. Thus, to machine an elemental area surrounding a point on the surface, the coordinates of the tool can be determined as follows. A vector equal to the radius of the ball-end mill is constructed normal to the elemental area surrounding the point. The coordinates of the end points of this vector give the position of the center of the cutter, as shown in Figure C-1.

In our case, the normal vector cannot be determined analytically since the die surface is defined only as a set of points. Therefore, two tangential vectors are constructed. The shape of the material path line on the die surface is known in analytical form. Thus, a vector $\vec{T}_1$ which is tangent to any point on a material path line is easily determined. The other tangential vector $\vec{T}_2$ is determined by taking an average slope of the boundary of the cross section at that point. A normal vector $\vec{n}$ is determined by cross product of the two vectors $\vec{T}_1$ and $\vec{T}_2$:

$$\vec{n} = \vec{T}_1 \times \vec{T}_2 \quad . \tag{C-1}$$

The cutter is moved over the flow lines in a manner shown in Figure C-1 and the coordinates of its center are determined by constructing the normal vectors at the various points defining the electrode surface. The detailed mathematics of the procedure, described here, are given in Appendix D.

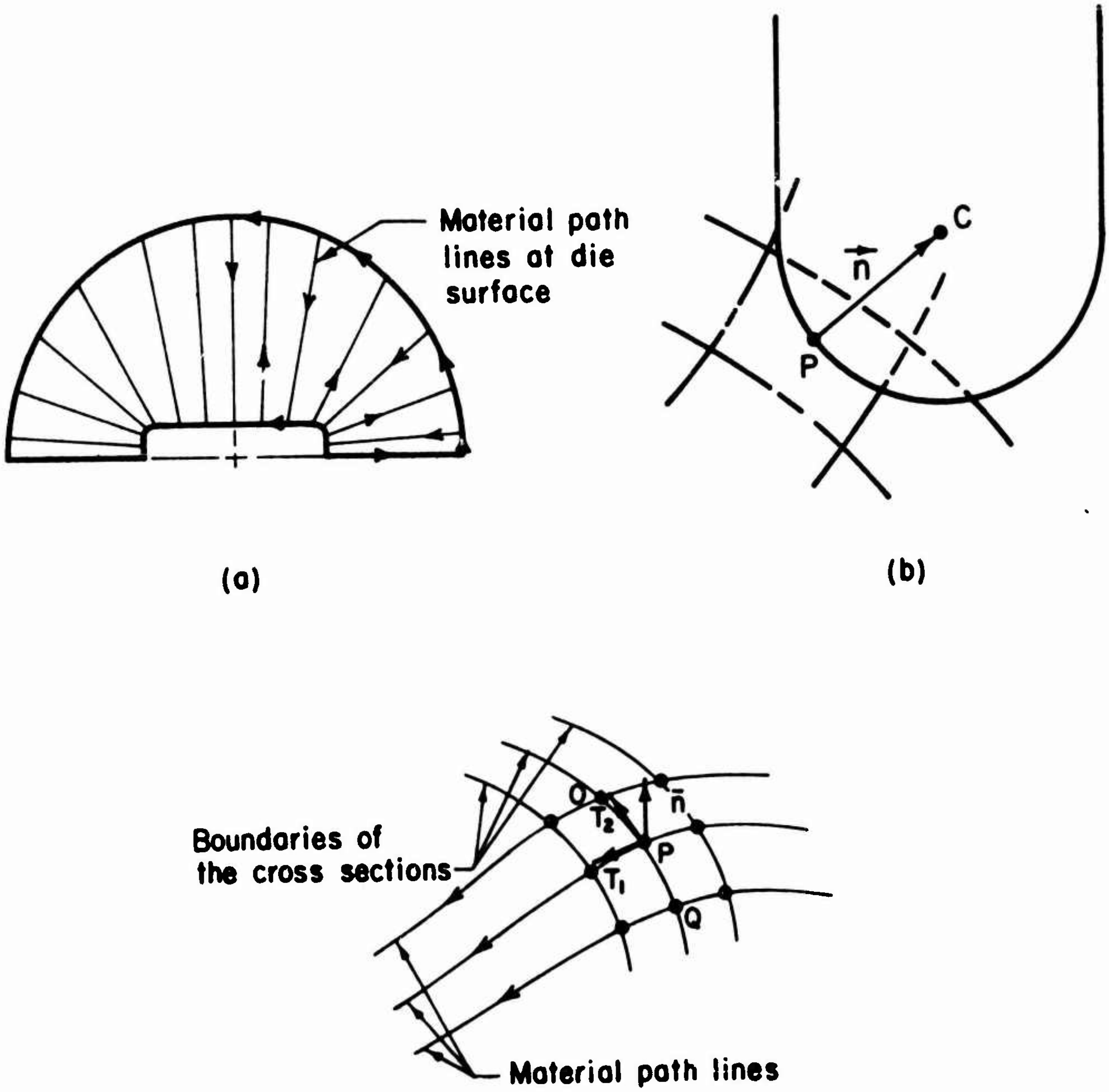



FIGURE C-1. NC MACHINING OF THE EDM ELECTRODE

(a) Cutter paths for machining the electrode surface

(b) Position of the tool with respect to an elemental area

(c) Construction of a vector normal to the electrode surface

# APPENDIX D

## DESCRIPTIONS OF GENERAL-PURPOSE COMPUTER PROGRAMS

## APPENDIX D

## DESCRIPTIONS OF GENERAL-PURPOSE COMPUTER PROGRAMS(*)

In this appendix, the basis of some of the routines used in the system of computer programs called "SHAPE" are presented.

### Method of Describing Extruded Shapes

The geometry of the extruded structural shapes used for military applications are relatively simple. In most cases, they are made up of straight-lines and circular arcs. A convenient method to describe such shapes is to define them as a polygon and to fit the desired radii at the corners and the fillets, as seen in Figure D-1.

In the system of computer programs "SHAPE", the center of the billet is chosen as the origin of the rectangular coordinate system and the coordinates of the points and associated radii are read in an anti-clockwise manner by subroutine REED. Subroutines INTRPL and FITARC fit the arcs at the corner and fillet points, respectively.

### Calculation of the Area of a Cross Section

The area of any polygon, as shown in Figure D-2, may be obtained by the formula:

$$A_S = \frac{1}{2}\left\{(x_2y_1-x_1y_2) + (x_3y_2-x_2y_3) + \dots + (x_ny_{n-1}-x_{n-1}y_n) + (x_1y_n-x_ny_1)\right\} \quad \text{(D-1)}$$

where $x_1$, $x_2$, ..., $x_n$ and $y_1$, $y_2$, ..., $y_n$ are coordinates of consecutive corners of the polygon with respect to a Cartesian coordinate system. A convenient

(*) A portion of this Appendix is based on a prior program, conducted by Battelle's Columbus Laboratories. It is included here for the sake of completeness.

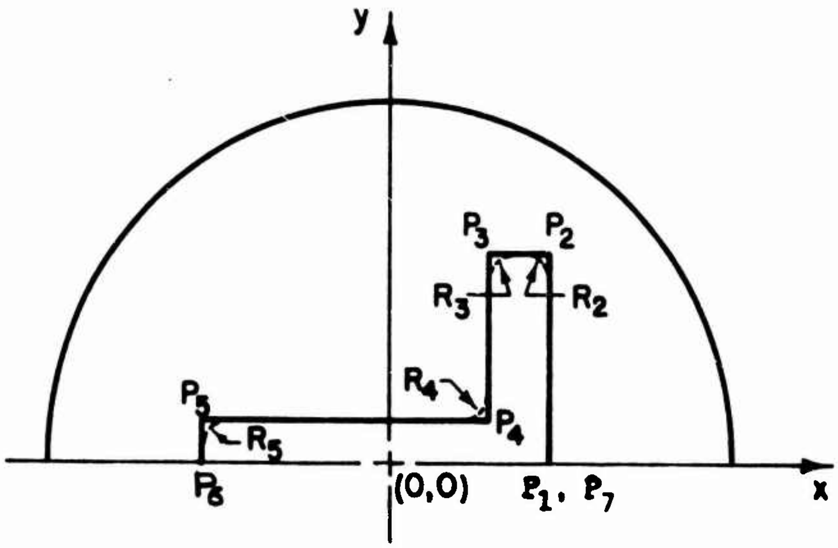



FIGURE D-1. PROCEDURE FOR REPRESENTING AN EXTRUDED SHAPE
(Only one-half of a symmetrical "T" shape is shown as an example)

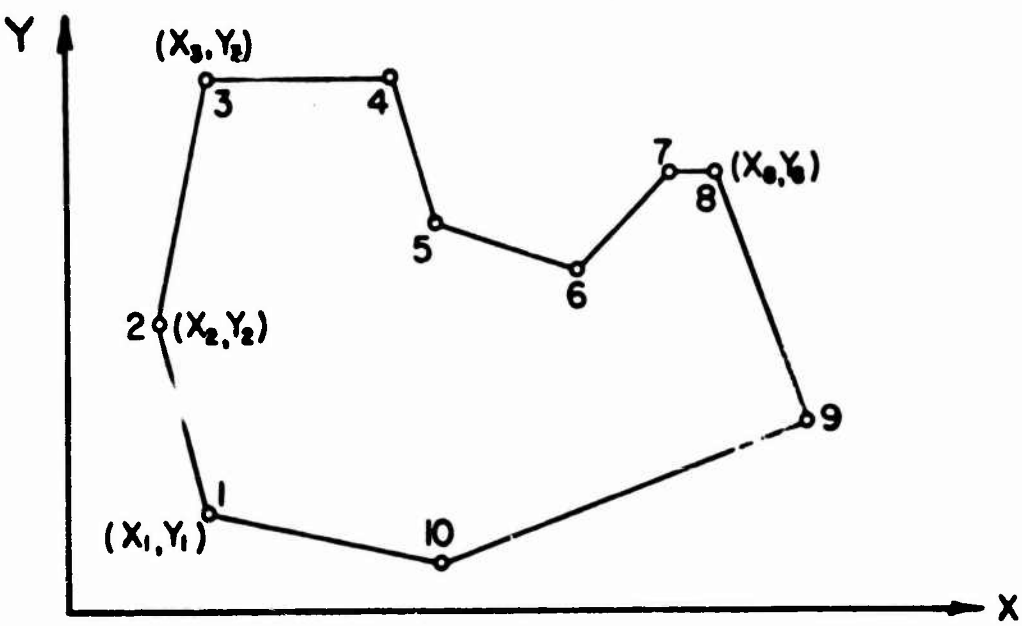



FIGURE D-2. DIAGRAM OF A POLYGON AND A RECTANGULAR COORDINATE SYSTEM DEFINING ITS CORNERS

## Fitting an Arc of a Circle

FITARC is a subroutine to determine the set of points on a specified arc such that when these points are joined by straight-lines, a fairly smooth curve is obtained. As shown in Figure D-3, given the coordinates $x_c$, $y_c$ of the center C, the radius R, the starting angular position, $\phi_b$, the included angle (arc angle), $\gamma$, and the desired resolution (i.e., the distance between any two consecutive points on the arc), the subroutine FITARC is programmed to generate coordinates of points along the desired arc. The arc distance between any two consecutive points is equal to the specified resolution. A fillet radius is specified as a positive radius since area due to the fillet is added to the cross-sectional area and a corner radius is specified as negative radius, since area due to it is subtracted.

## Mathematical Background for Fitting an Arc

The following is a summary of the mathematical derivations used in programming the subroutine FITARC. All the symbols are defined in Figure D-3, and the same figure will be referred to, implicitly, throughout this section.

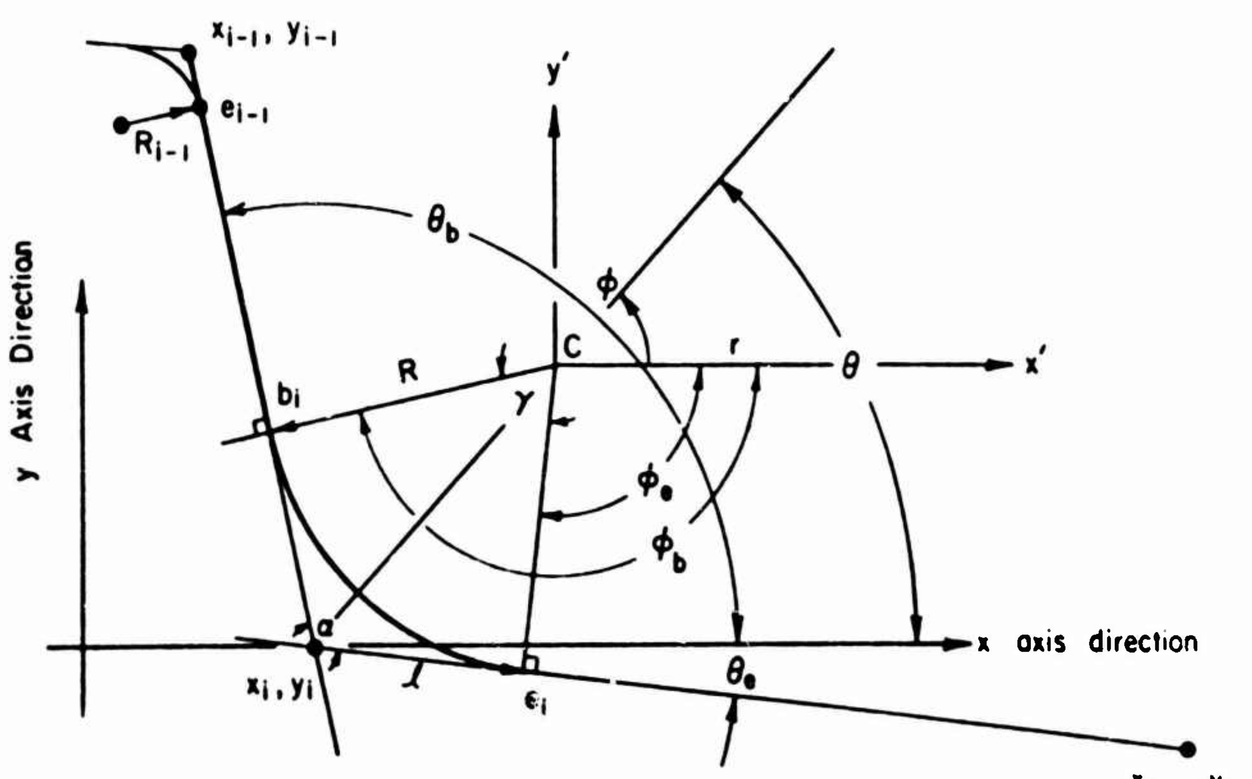



FIGURE D-3. FITTING A CIRCULAR ARC BETWEEN TWO INTERSECTING LINES

The coordinates of the center of the arc are given by

$$x_c = x_i + \frac{R}{\cos \frac{\gamma}{2}} \cos \theta \tag{D-2}$$

$$y_c = y_i + \frac{R}{\cos \frac{\gamma}{2}} \sin \theta \quad , \tag{D-3}$$

where $\theta$ is determined by

$$\theta = (\theta_b + \theta_e)/2 \tag{D-4}$$

and

$$\theta_b = \text{arc tan } [(y_{i-1} - y_i)/(x_{i-1} - x_i)] \tag{D-5}$$

$$\theta_e = \text{arc tan } [(y_{i+1} - y_i)/(x_{i+1} - x_i)] \quad . \tag{D-6}$$

The angle $\gamma$ may be calculated by

$$\gamma = \pi - \alpha \tag{D-7}$$

and

$$\alpha = \text{arc cos} \left[\frac{B^2 + C^2 - A^2}{2BC}\right] \tag{D-8}$$

where

$$A = \left[\left(x_{i+1} - x_{i-1}\right)^2 + \left(y_{i+1} - y_{i-1}\right)^2\right]^{1/2} \tag{D-9}$$

$$B = \left[\left(x_{i+1} - x_i\right)^2 + \left(y_{i+1} - y_i\right)^2\right]^{1/2} \tag{D-10}$$

$$C = \left[\left(x_{i-1} - x_i\right)^2 + \left(y_{i-1} - y_i\right)^2\right]^{1/2} \quad . \tag{D-11}$$

The coordinates of the points $e_i$ and $b_i$ may be determined by

$$x_b = x_i + \ell \cos \theta_b \tag{D-12}$$

$$y_b = y_i + \ell \sin \theta_b \tag{D-13}$$

and

$$x_e = x_i + \ell \cos \theta_e \tag{D-14}$$

$$y_e = y_i + \ell \sin \theta_e \tag{D-15}$$

where

$$\ell = R \quad \tan \frac{\gamma}{2} \quad . \tag{D-16}$$

The starting angle of an arc, $\varphi_b$, is given by

$$\varphi_b = \text{arc tan} \left[ \left( y_h - y_c \right) / \left( x_b - x_c \right) \right] \quad . \tag{D-17}$$

Let

r = resolution in thousands of an inch.

$$n = \text{The integer part of } [1000\ R\gamma/r + .5] \tag{D-18}$$

where n is the number of points that will be determined on the arc. Then $\delta$, the incremental angle, is given by

$$\delta = \frac{\gamma}{n} \cdot (\text{sign of } R) \quad . \tag{D-19}$$

$\varphi_b$ is incremented by $\delta$, n times in order to determine the coordinates of n points on the arc by using the equations

$$x_{aj} = x_i + R \cos \varphi \tag{D-20}$$

$$y_{aj} = x_i + R \sin \varphi \tag{D-21}$$

where

$j = 1, 2, \ldots, n.$

## Properties of Straight-Lines

### Equation of a Line Joining Two Points

The equation of a line joining two points $(x_1, y_1)$ and $(x_2, y_2)$ in a plane xy is:

$$(y-y_1)\ (x_2-x_1) = (x-x_1)\ (y_2-y_1) \quad .$$

One may write the above equation in the following forms:

$$y = y_1 + (x-x_1) \left(\frac{y_2 - y_1}{x_2 - x_1}\right) \quad \text{for } x_2 \neq x_1 \text{ ,} \tag{D-22}$$

$$\text{or} \quad x = x_1 + (y-y_1) \left(\frac{x_2 - x_1}{y_2 - y_1}\right) \quad \text{for } y_2 \neq y_1 \text{ .}$$

### Intersection of Two Given Lines

The coordinates $(x_1, y_1)$ of the point of intersection of two lines $a_1x + b_1y + c_1 = 0$ and $a_2x + b_2y + c_2 = 0$ are:

$$x_1 = \frac{b_1c_2 - b_2c_1}{a_1b_2 - a_2b_1} \text{ , } \quad y_1 = \frac{c_1a_2 - c_2a_1}{a_1b_2 - a_2b_1} \text{ ,} \tag{D-23}$$

provided $a_1/a_2 \neq b_1/b_2$. When $a_1/a_2 = b_1/b_2$, the lines are parallel and do not intersect.

Points on the Same Side or on the Opposite Side of a Straight-Line

Points $(x_1,y_1)$ and $(x_2,y_2)$ are on the same side of the line $ax + by + c = 0$ if

$$A = - \frac{ax_1 + by_1 + c}{ax_2 + by_2 + c} < 0 \quad . \tag{D-24}$$

They are on opposite sides if A is positive.

Fitting a Curve Between Two Points

To fit a particular curve between two points P $(x_1,y_1,z_1)$ and Q $(x_2,y_2,z_2)$ such that this curve lies in a plane perpendicular to x-y plane, the following procedure can be adopted. We set up a cylindrical coordinate system $(r,\theta,\xi)$ with origin at Q' such that $\theta$=0 is a plane passing through points P,Q',Q and perpendicular to xy plane. In $(r,\xi)$ plane, let the equation of the curve be

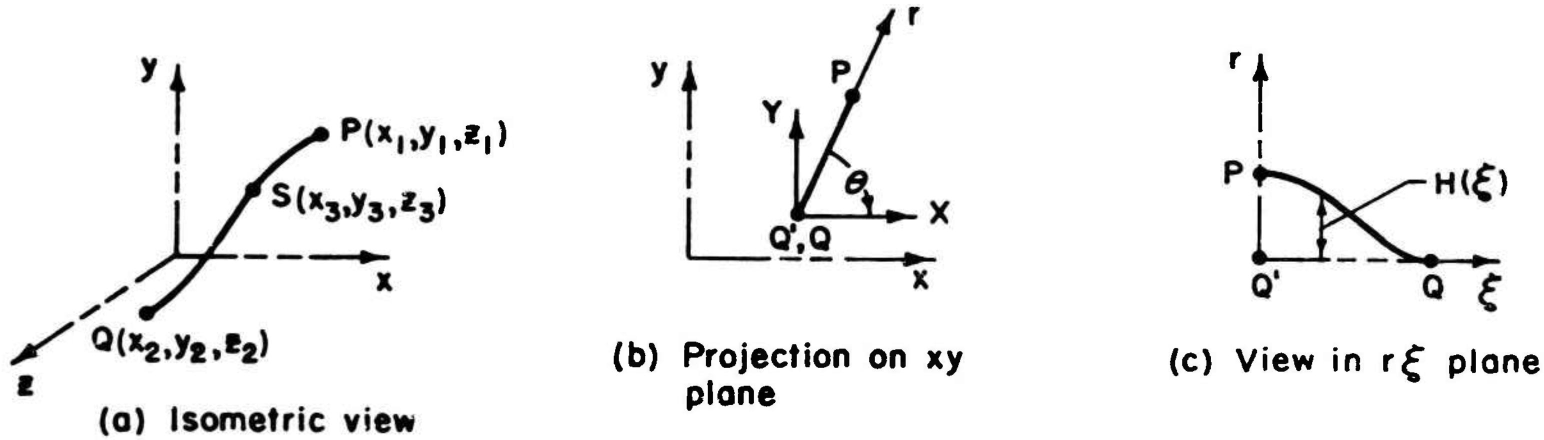
$$r = H(\xi) \quad , \tag{D-25}$$

where $H(\xi) = A = [(x_2-x_1)^2 + (y_2-y_1)^2]^{1/2}$ for $\xi = 0$, and
$H(\xi) = 0$ for $\xi = z_2-z_1$.

x and y coordinates $(x_3,y_3)$ of a point S, whose z coordinate is $z_3$, can be determined from the relation:

$$\begin{aligned} x_3 &= x_2 + (x_1-x_2)\ (R/A) \\ y_3 &= y_2 + (y_1-y_2)\ (R/A) \ , \end{aligned} \tag{D-26}$$

where $R = H(\xi)$ at $\xi = z_3-z_1$.




(a) Isometric view

(b) Projection on xy plane

(c) View in rξ plane

FIGURE D-4. REPRESENTATION OF A CURVE BETWEEN TWO POINTS IN A 3-D SPACE

Polynomial Curve

The polynomial curve which fits the point P and Q is given by:

$$r = H(\xi) = A + (C_1L^2 + 2\,C_2L^3 - 3A/L^2)\,\xi^2$$

$$+ (2A/L^3 - 2C_1L - 3C_2L^2)\,\xi^3 + C_1\xi^4 + C_2\xi^5 \quad ,$$

where $L = z_2 - z_1$.

Straight-Line

The equation of a straight-line fitted between the points P and Q is given by:

$$r = H(\xi) = A\,\frac{(L - \xi)}{L} \quad .$$

## Vector Tangent to Material Path Line

Equation (D-25) represents the equation of a material path line between points $P(x_1,y_1,z_1)$ and $Q(x_2,y_2,z_2)$. Substituting for $r$ in terms of x and y, Equation (D-25) may be written as:

$$(x-x_2)^2 + (y-y_2)^2 = H^2(\xi) \ , \qquad \text{(D-27)}$$

where $\dfrac{y-y_2}{x-x_2} = \dfrac{y_2-y_1}{x_2-x_1}$ .

Equation (D-27) may be rewritten in the following form:

$$\begin{aligned} x-x_2 &= (x_1-x_2)\,H(\xi)/A \\ y-y_2 &= (y_1-y_2)\,H(\xi)/A \quad , \end{aligned} \qquad \text{(D-28)}$$

where A is given by Equation (D-25).

A vector tangent to a curve is, by definition:

$$\vec{T}_1 = (dx/dz)\vec{i} + (dy/dz)\vec{j} + \vec{k} \ .$$

Substituting for the derivations (dx/dz) and (dy/dz):

$$\vec{T}_1 = \frac{1}{A}(x_1 - x_2)\ H'(\xi)\vec{i} + \frac{1}{A}(y_1 - y_2)\ H'(\xi)\vec{j} + \vec{k} \ , \qquad \text{(D-29)}$$

where $\quad H'(\xi) = dH(\xi)/d\xi.$

## Vector Tangent to a Point on the Boundary of a Die Cross Section

In the numerical definition of the die surface, the boundary of a die cross section is defined by a number of points. Let $P(x_1,y_1)$, $Q(x_2,y_2)$ and $R(x_3,y_3)$ be a set of three points. To determine a vector at Q which is tangent to the boundary, the following procedure is adopted. The angle $\theta$, which the vector makes with the x axis, is approximated as mean of the angles $\theta_1$ and $\theta_2$, which the lines PQ and QR make with the x axis. Thus,

$$\theta = \frac{1}{2}\left[\tan^{-1}\left(\frac{y_2 - y_1}{x_3 - x_2}\right) + \tan^{-1}\left(\frac{y_3 - y_2}{x_3 - x_2}\right)\right] \ . \qquad \text{(D-30)}$$

The tangent vector is given by:

$$T_2 = \vec{i} + \tan\theta\ \vec{j} \ . \qquad \text{(D-31)}$$

## Vector Normal to Two Vectors

A vector $\vec{N}$ normal to two vectors $\vec{T}_1$ and $\vec{T}_2$ is given by the vector cross product as:

$$\vec{N} = \vec{T}_1 \times \vec{T}_2$$

or $\quad C_x\vec{i} + C_y\vec{j} + C_z\vec{k} = (A_yB_z - A_zB_y)\ \vec{i} + (A_zB_x - A_xB_z)\ \vec{j} + (A_xB_y - A_yB_x)\ \vec{k} \ ,$

where
$$\vec{T}_1 = A_x\vec{i} + A_y\vec{j} + A_z\vec{k}$$
$$\vec{T}_2 = B_x\vec{i} + B_y\vec{j} + B_z\vec{k}$$
$$\vec{N} = C_x\vec{i} + C_y\vec{j} + C_z\vec{k}.$$

## Undercutting by the Tool During Machining of a Surface

In NC machining, the cutter is moved over the surface to be machined in a specified path. There is a possibility that while machining a particular portion of the surface, the tool surface may undercut or gouge some other portion of the surface. Mathematically, it is simple to check for gouging by a ball-end mill. A spherical tool will cut a surface, if the distances between the tool center and the points defining the surface are less than the radius of the tool. Practically, it will be time consuming and very inefficient to check undercutting over the whole surface for every single position of the tool. Therefore, the range of the surface over which the possibility of undercutting is checked for is limited to a small portion of the surface being cut.

In subroutine CHECKNC, for each position of the tool, the distances between the center of the spherical portion of the tool and a number of points surrounding the point on the surface being machined are calculated. If any of the distances are found to be less than the radius of the tool, undercutting is predicted and the designer is warned. In interactive mode, the designer can reduce the size of the ball-end mill to avoid undercutting.

APPENDIX E

## SHAPE - A SYSTEM OF PROGRAMS TO ANALYZE THE SHAPE-EXTRUSION PROCESS

# APPENDIX E

## SHAPE - A SYSTEM OF PROGRAMS TO ANALYZE THE SHAPE-EXTRUSION PROCESS

The computer programs developed to obtain the optimum die shape, to calculate the extrusion and die pressures, and to obtain coordinate data for numerical-control machining of the extrusion die are grouped under the name "SHAPE". This software package can be used either in batch mode, or in interactive mode. It is written in FORTRAN-IV language.

### Description of SHAPE

SHAPE is written in an overlay structure. As shown in Figure E-1, it has a main overlay and three primary overlays. Each of these overlays perform specific functions during the execution of the program.

### Overlay (SHAPE,0,0)

This main overlay assigns default values to unspecified variables, reads values of variables specified by the designer, and controls the other overlays. The subroutines in this overlay are all utility routines and are called by routines in other overlays.

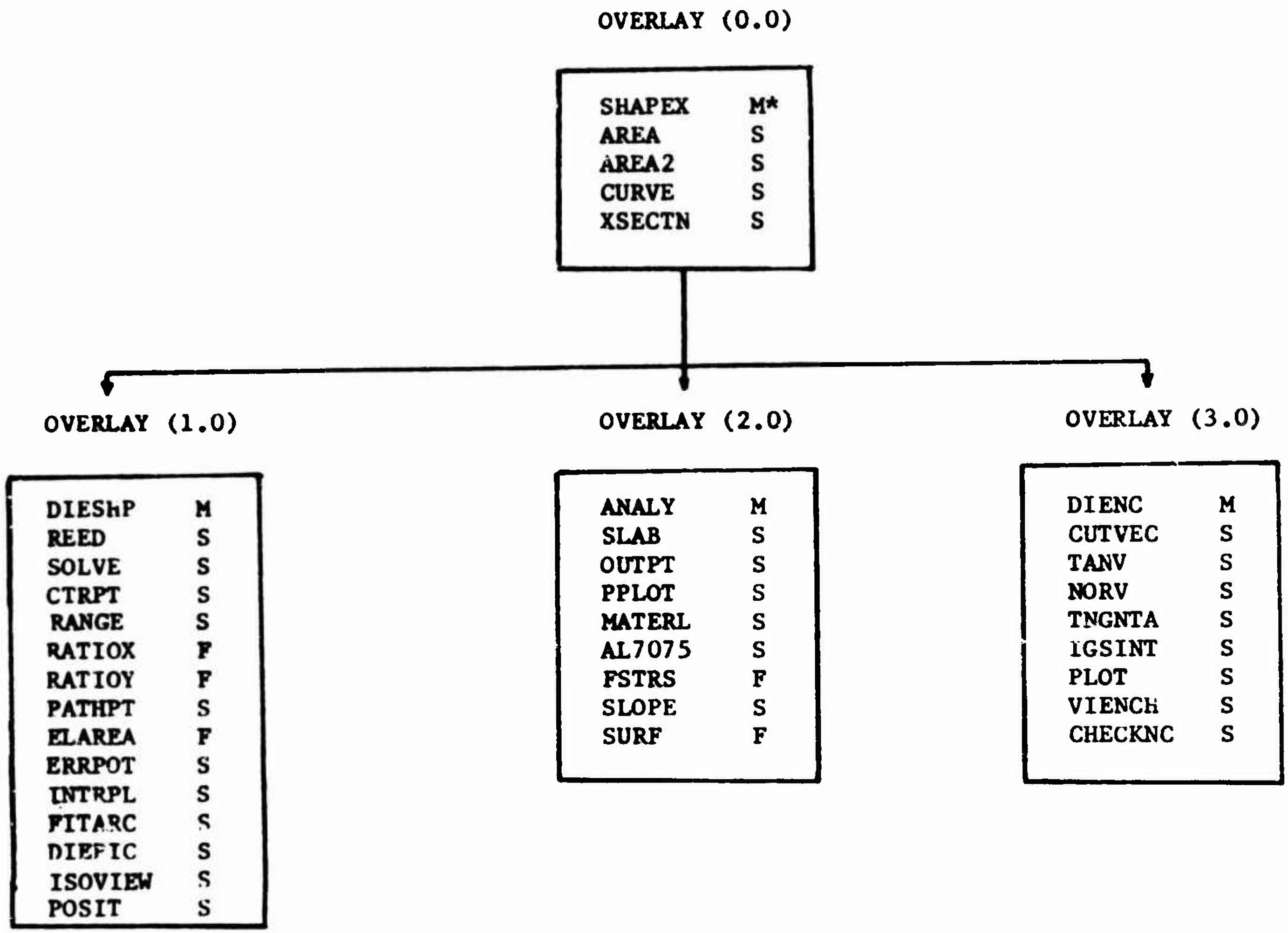
The input of the variables, specified by the designer, is accomplished via namelist IDATA described in the next section.

### Overlay (SHAPE,1,0)

This primary overlay performs the following tasks:

(1) Reads the coordinate data for describing the product shape.

(2) Fits radii to corner and fillets of the product shape defined as a polygon.




*M: Main Program S: Subroutine

FIGURE E-1. OVERLAY STRUCTURE OF THE SYSTEM OF PROGRAMS "SHAPE"

(3) Moves the shape with respect to the billet center, if desired.

(4) Defines the die shape as a set of points in 3-D space.

The position of the neutral axis, if not determined numerically, is read via namelist CTRPTS in this overlay.

Overlay (SHAPE,2,0)

This second primary overlay performs the load calculation. For given values of extrusion-process variables (specified by Namelist IDATA in main overlay), the total extrusion pressure and its components, total extrusion load and die pressure distribution are determined. In addition, such parameters as cross-sectional area of the shape, extrusion ratio, perimeter of the shape, and surface area of the die are computed.

Overlay (SHAPE,3,0)

The third primary overlay calculates the coordinates of the cutter paths for NC machining of the EDM electrode. The overlay checks for undercutting or gouging by the tool. In the interactive mode, if it is determined that the specified tool will undercut, the designer is warned and given the option to change the size of the cutter.

## Input by NAMELIST

The input of extrusion-process variables is accomplished by "NAMELIST". Defining variables as namelist elements gives the flexibility of specifying only those that are needed. Almost every namelist element is assigned a default value whenever feasible. Thus, SHAPE will automatically use the default values of unspecified parameters. When entering a namelist, the first column must be left blank and a dollar sign must be entered in column two.

NAMELIST/IDATA

IDATA is read by program SHAPEX. This is used to read in the initial values for almost all the variables which the designer may wish to specify.

Default values for each of the variables listed below are given at the end of the description in parenthesis.

NAXIAL : Number of divisions in which the length of the die is divided. This parameter is used in numerical definition of the die surface and for subsequent stress analysis (10).

NCURVE : Code to specify the type of curve fitted along assumed path lines (1)
- = 1; polynomial
- = 2; straight line.

RAD : Radius of the billet, inch (1.0).

AL : Length of the die, inch (1.0).

ANGLIM : Angle defining portion of the die (or extrusion process) to be analyzed, degree (180.0).

NDIV : Number of radial divisions in which the die surface is divided for the purpose of defining die surface numerically.

IMATER : Code to specify the material being extruded (8).
- = 1 for titanium alloy Ti-6Al-4V.
- = 2 for aluminum alloy Al 7075.
- = 3 for aluminum alloy Al 2017.
- = 4 for steel alloy S4337.
- = 5 for 99.97% pure aluminum.
- = 6 for lead.
- = 7 for OFHC copper.
- = 8 for a perfectly plastic material having a constant flow stress of 10,000 psi.

IUNIT : Code to specify the category of the extrusion shape (1).
- = 1; rectangular, Tee and similar shapes having at least one plane of symmetry.
- = 2; shapes with no plane of symmetry.

XMOV,YMOV: Displacement in inches along x and y axis, respectively, of the extruded shape with respect to the billet axis (0.0,0.0).

C1,C2 : Coefficients used in the definition of the polynomial curve (0.0,0.0).

NSKIP : Number of extrusion shapes that may be skipped before reading in the input data on product shape (0).

RT : Radius of the ball-end mill, inch (0.25).

ALAPPX : An initial guess of the optimal die length, inch (1.0).

LD : Die-land length, inch (0.061).

LO : Initial length of the billet, inch.

MC : Friction shear factor at material-container interface (0.2).

MD : Friction shear factor at material-die interface (0.3).

VO: : Ram speed, inch/second (20.).

TEMP : Initial billet temperature, F (800.0).

The following are logical variables; that is, they are either .TRUE. or .FALSE.

DETCTR : If DETCTR = .TRUE., the program will calculate the position of the neutral axis for IUNIT = 1. If DETCRT = .FALSE., program will read the positions of the neutral axes via NAMELIST/CTRPTS (.TRUE.).

DEBUG : If DEBUG = .TRUE., values calculated in various subroutines will be printed for the purpose of debugging the program (.FALSE.).

OPTLEN : If OPTLEN = .TRUE., the optimal length of the die is to be determined (.TRUE.).

CHKINT : If CHKINT = .TRUE., the program checks for undercutting by the ball-end mill in machining the desired surface (.FALSE.).

MANUAL : If MANUAL = .TRUE., the coordinates and the radii needed to define the shape are entered via TTY (.FALSE.).

ANALYS : If ANALYS = .TRUE., the stress analysis is to be performed (.TRUE.).

DETAIL : If DETAIL = .TRUE., program prints intermediate results on TAPE1. (.FALSE.).

BATCH : If BATCH = .TRUE., the program will run on batch mode. If BATCH = .FALSE, the program will run on interactive mode.

NC : If NC = .TRUE., the portion of the computer program on numerical control (NC) machining of the EDM electrode will be executed (.TRUE.).

TAPE : If TAPE = .TRUE., the coordinates of the ball-end mill cutter are stored in Tape 3 (.TRUE.).

ISOMET : If ISOMET = .TRUE., in the interactive mode, an isometric view of the die surface will be plotted.

NAMELIST/CTRPTS

If the user wishes to specify the positions of the neutral axes himself instead of determining them, DETCTR is set equal to .FALSE., and the coordinates of the positions of the neutral axes are entered via NAMELIST/CTRPTS. XCTR, YCTR are single dimensioned arrays of size 2.

XCTR,YCTR: x and y coordinates, in inches, of the positions of the neutral axes for the different portions of the deformation zone (0.0,0.0).

XMOV,YMOV: Displacements, in inches, along x and y axis, respectively, of the extrusion shape with respect to the billet axis (0.0,0.0).

## Main Overlay - Overlay (0,0)

The program SHAPEX of the main overlay serves essentially as a coordinating routine which collects the input data and calls other overlays as necessary. Links between the main overlay and other primary overlays are maintained through common locations.

## Subroutine AREA

**Purpose:** This subroutine calculates the area of a polygon.

**Calling Sequence:** Call AREA (X,Y,N,A) where X and Y are single-dimensioned arrays of size N.

**Input:** X,Y: X and Y coordinates, respectively, of the corner points of the polygon.

N: Total number of corner points in the polygon.

**Output:** A: Area of the polygon.

**Basis:** See Appendix D.

## Subroutine AREA2

**Purpose:** This subroutine calculates the area of a polygon. It performs essentially the same calculations as subroutine AREA; however, it uses a different calling sequence.

**Calling Sequence:** Call AREA 2 (X1,Y1,XN,YN,X,Y,K,A) where X and Y are single-dimensioned arrays of size K.

**Input:** X1,Y1: X and Y coordinates, respectively, of the first point of the polygon.

XN,YN: X and Y coordinates, respectively, of the last point of the polygon.

X,Y: X and Y coordinates, respectively, of remaining K points of the polygon.

**Output:** A: Area of the polygon.

**Basis.** See Appendix D.

## Subroutine CURVE

**Purpose:** This subroutine fits the desired curve between two points $(X_1,Y_1,Z_1)$ and $(X_2,Y_2,Z_2)$, and computes X and Y coordinates, (XX,YY) of a point on this curve, whose Z coordinate is ZZ.

<u>Calling Sequence</u>: Call CURVE (NCODE, X1,Y1,Z1,X2,Y2,Z2,XX,YY,ZZ, C1,C2).

<u>Input</u>: (X1,X2,Y1,Y2,Z1,Z2): X,Y and Z coordinates, respectively, of the two points between which a curve is to be fitted.

NCODE: Determines the type of curve.

= 1; polynomial curve.

= 2; straight-line.

ZZ: Z coordinate of a point on the curve.

C1,C2: Coefficients which vary the shape of the polynomial curve.

<u>Output</u>: XX,YY: X and Y coordinates, respectively, of a point on the curve whose Z coordinate is ZZ.

<u>Basis</u>: See Appendix D.

<u>Subroutine XSECTN</u>

<u>Purpose</u>: This subroutine determines points on the die cross section at various locations along the die length.

<u>Calling Sequence</u>: Call XSECTN (NCURVE, NAXIAL, IERR).

<u>Input</u>: NCURVE: Determines the type of curve to be fitted along material path lines.

= 1; polynomial curve.

= 2; straight-line.

NAXIAL: Number of divisions along the axial direction. Input of other variables is through COMMON statement.

<u>Output</u>: Output of points on the cross section is via COMMON statement.

IERR: If > 1, some error occurred in computing the points on the cross section.

<u>Basis</u>: See Appendix D.

## First Primary Overlay - Overlay (1.0)

The main program in this primary overlay is DIESHP. Along with other routines, it reads the coordinate data describing the extrusion shape, fits the radii at the corners and fillets, moves the shape with respect to the extrusion axis. Further, DIESHP determines the position of the neutral axis if desired, computes the positions of the end points on the material path lines, fits the curves between end points of the material path lines and defines the shape of the die as a set of points in a three-dimensional space.

### Subroutine REED

Purpose: This subroutine reads the input data on the radii and coordinates of the points defining the extrusion shape.

Calling Sequence: Call REED (X,Y,R,NIP,IERR,MANUAL,BATCH), where X,Y and R are single-dimensioned arrays of size 50.

Input: X,Y: X and Y coordinates, respectively, of the points defining the extrusion shape.

R: Radius to be fitted at each corner or fillet to form the shape.

MANUAL: If MANUAL = .TRUE., the data (X,Y,R) are entered via TTY.

BATCH: If BATCH = .TRUE., the data (X,Y,R) are read from TAPE 2.

Output: NIP: Number of points that were read.

IERR: > 1 if an error occurred in reading the input data.

Basis: See Appendix D.

### Subroutine SOLVE

Purpose: This subroutine finds the solution of an Equation F(x) = 0., within a specified range of x.

Calling Sequence: Call SOLVE (F,XLOW,XHIGH,LIMITX,LIMITF,XSOLVE,IERR).

Input: F: User's specified external function F(x). x is a dummy variable.

XHIGH,XLOW: Limits of the range of the independent variable x, within which a solution is sought.

LIMITF: Admissible inaccuracy in the solution of equation F(x) = 0. Solution is considered obtained when ABS(F(x)) < LIMITF.

LIMITX: Admissible inaccuracy in the value of XSOLVE.

Output: XSOLVE: The value of independent variable x which solves the equation.

IERR: = 1 when XSOLVE is obtained within the prescribed range of variable x.

> 1 if some error occurred and a solution was not obtained.

Basis: The subroutine uses the method of interval halving to find the solution. Reference (13) describes in detail this method.

Subroutine CTRPT

Purpose: This subroutine determines the position of the neutral axis.

Calling Sequence: Call CTRPT (IERR).

Input: Input of variables is through COMMON statement. RATIO is used as an EXTERNAL function in the subroutine.

Output: XC: x coordinate of the neutral axis.

YC: y coordinate of the neutral axis.

IERR: If > 1, error occurred in calculating XC or YC.

Output of XC and YC is through COMMON statement.

Basis: See Appendix A.

## Subroutine RANGE

**Purpose:** This subroutine determines the maximum and minimum values among an array of real numbers.

**Calling Sequence:** Call RANGE (Z,N,ZMIN,ZMAX)

**Input:** Z: A single dimensioned array of real numbers.
N: Size of the array.

**Output:** ZMIN: Minimum value among Z.
ZMAX: Maximum value among Z.

## Function RATIOX(X)

**Purpose:** In conjunction with subroutine CTRPT, this function calculates the x coordinate of the neutral axis.

**Input:** X: Chosen position of the neutral axis along x axis.
Input of other variables is through COMMON statements.

**Output:** RATIOX: The difference between the overall area reduction and the area reduction in the portion of the deformation zone on one side of plane x = x.

**Basis:** See Appendix A.

## Function RATIOY(Y)

**Purpose:** In conjunction with subroutine CTRPT, this function calculates the y coordinate of the neutral axis.

**Input:** Y: Chosen position of the neutral axis along y axis.
Input of other variables is through COMMON statements.

**Output:** RATIOY: The difference between the overall area reduction and the area reduction in the portion of the deformation zone on one side of the plane y = y.

**Basis:** See Appendix A.

## Subroutine PATHPT

Purpose: This subroutine calculates the end point of a material path line on the boundary of the exit cross section.

Calling Sequence: Call PATHPT (AREAB,XSS,YSS,IERR).

Input: AREAB = Area of a portion of the billet cross section. Input of other variables is through COMMON statements. ELAREA is used as EXTERNAL FUNCTION in the subroutine.

Output: XSS,YSS: X and Y coordinates, respectively, of the end point.

IERR: If > 1, error occurred in calculating XSS or YSS.

Basis: See Appendix A.

## Function ELAREA (Z)

Purpose: For a given x or y coordinate of a point on the exit boundary, this function determines the difference in overall area reduction ($A_f/A_o$) and the area reduction of an element of the initial billet cross section. Together with subroutine PATHPT, it determines the end point of a material path line on the exit boundary.

Input: Z: x or y coordinate of the assumed end point of the material path line. Input of other variables is through COMMON statement.

Output: ELAREA: The difference in overall area reduction and the area reduction of an element of the billet cross section.

Basis: See Appendix A.

## Subroutine ERRPOT

Purpose: This subroutine prints on the output device any errors that occur during the execution of the program DIESHP.

Calling Sequence: Call ERRPOT (IERR).

Input: IERR: If > 1, error occurred. Depending on the value of IERR, the information on the nature of the error is printed on the output device.

## Subroutine INTRPL

Purpose: For a polygonal cross section defined by a series of fillet or corner coordinates and the associated radii, this subroutine calculates the points which actually lie on the perimeter of the cross section.

Calling Sequence: Call INTRPL (XPLOT,ZPLOT,NPLOT,XPS,ZPS,RPS,IPS), where XPLOT and ZPLOT are single-dimensioned arrays of size NPLOT; XPS,ZPS and RPS are single-dimensioned arrays of size IPS.

Input: XPS,ZPS: x and y coordinates, respectively, of the points defining the polygonal cross section.

RPS: Radii at fillets or corners of the polygonal cross section.

IPS: Number of corner and fillet points.

Output: XPLOT,ZPLOT: x and y coordinates of points on the perimeter of the cross section.

NPLOT: Number of such points.

Subroutine FITARC

Purpose: Given three points and a radius, this subroutine defines a certain number of equispaced points on an arc tangent to the two lines defined by the three points.

Calling Sequence: Call FITARC (X1,Z1,X2,Z2,X3,Z3,RD,XP,ZP,NP,RES, LIM,IFLAG), where XP and ZP are single-dimensioned arrays of size NP.

Input: (X1,Z1), (X2,Z2), (X3,Z3): coordinates (x,y) of the three points.

RD: Radius of the arc to be fitted.

RES: Resolution or distance between the points on the arc.

LIM: Maximum allowable number of points on the fitted arc.

IFLAG: If = 1, actual number of points did not exceed LIM.
If $\geq$ 1, actual number exceeded LIM.

XP,ZP: Coordinates (x and y) of points on the arc.

NP: Actual number of such points.

Subroutine DIEPIC

Purpose: Plots the shapes of the billet and the product, material path lines, and die cross sections on CRT display screen. This routine uses other routines of the IGS package and is hardware dependent.

Subroutine ISOVIEW

Purpose: Draws an isometric view of the die shape. This routine also uses other standard routines of the IGS package. It is also hardware dependent.

Subroutine POSIT

Purpose: This subroutine is used to position any writing on CRT display screen.

## Second Primary Overlay - Overlay (2.0)

The main program of this primary overlay is ANALY. Along with other routines, ANALY calculates the extrusion pressure, optimal length of the die and mean-die pressure distribution. In interactive mode, a plot of extrusion pressure versus die length is drawn.

### Subroutine SLAB

Purpose: This routine computes the various components of the extrusion pressure and the total extrusion pressure.

Input and Output: Is through common locations.

Basis: See Appendix B.

### Subroutine OUTPT

Purpose: This routine writes the input and output information concerning the load calculation.

### Subroutine PPLOT

Purpose: This routine is used in the interactive mode to plot the maximum extrusion pressure as function of the die length. It uses other routines of IGS package and is hardware dependent.

Calling Sequence: Call PPLOT (XMIN,YMIN,XMAX,YMAX,ANSWER).

Input: (XMIN,YMIN): (XMAX,YMAX) Coordinates defining the size of the subject space. Other input is through common locations.

Output: ANSWER: If ANSWER = YES, the designer selects the optimal length of the die. Other output is through common locations.

### Subroutine MATERL

Purpose: In conjunction with the subroutines Ti-6Al-4V, AL2075, AL2017, S4337, ALUMSP, LEAD, OFHC, and ALOYSP, it

calculates the flow stress of the desired material as a function of the temperature, strain, and strain rate.

Input: IMATER: Code to specify the material being extruded.

= 1 for titanium alloy Ti-6Al-4V.

= 2 for aluminum alloy AL7075.

= 3 for aluminum alloy AL2017.

= 4 for steel alloy S4337.

= 5 for 99.97% pure aluminum.

= 6 for lead.

= 7 for OFHC copper.

= 8 for a perfectly plastic material having a constant flow stress of 10,000 psi.

TEMP: Initial temperature of extrusion.

STRAIN: Value of effective strain at which the flow stress is to be determined.

STRRAT: Value of strain rate.

Output: FSTRES: Flow stress of the material.

Subroutine AL7075

Purpose: Flow stress data for aluminum alloy AL7075 at various temperatures and different strain values are stored in this routine and is called whenever flow stress data for AL7075 is required at a particular combination of strain and temperature.

Function FSTRS

Purpose: This function routine performs the interpolation in determining the values of m and c in flow stress calculation. (Flow stress is defined as function of strain, strain rate and temperature in terms of the coefficients m and c). To interpolate the data for correct temperature value, library subroutine AITKN is used.

Subroutine SLOPE

Purpose: This subroutine is used to determine slopes of the material path lines at the entrance and the exit of the die.

Input: NCODE: Code to define the type of curve fitted between the end points of the material path line.

(X1,Y1,Z1): (x,y,z) coordinates of the end points
(X2,Y2,Z2) of the material path line.

N2: N2 = 2 is always used.

C1,C2: Coefficients of the polynomial curve.

Output: HDZ: Slopes of the path lines at the die entrance and the die exit.

Function SURF

Purpose: This function calculates the area of a triangle. It is used in calculating friction at the die surface.

(X1,Y1,Z1): Corner points of the triangle.
(X2,Y2,Z2)
(X3,Y3,Z3)

Third Primary Overlay - Overlay (3.0)

DIENC is the main program of this overlay. It determines the cutter path for NC machining of EDM electrodes. Using other routines, it computes the coordinates of the position of the cutter as the cutter is moved over the die surface in a predetermined manner. The position of the cutter is calculated by constructing a vector normal to the surface from two tangent vectors. DIENC also checks for any undercutting by the tool.

Subroutine CUTVEC

Purpose: This routine computes vectors normal to the die surface along a material path line. It uses other routines of the overlay. RX,RY,RZ are single-dimensioned arrays of size 22.

Calling Sequence: CUTVEC (NCODE,N2,N1,RX,RY,RZ,I).

Input: NCODE: Code to specify the curve fitted between the material end points.

N2: Number of points defining the die surface along a material path line.

N1: Number of points defining the die surface along a cross-sectional boundary.

I: Number specifying the material path line.

Other input is via common locations.

Output: (RX,RY,RZ): (x,y,z) components of the normal vectors.

Basis: See Appendix D.

Subroutine TNGNTA

Purpose: This subroutine determines tangent vector at points along a material path line.

Calling Sequence: Call TNGNTA (NCODE,X1,Y1,Z1,X2,Y2,Z2,N2,C1,C2, AX,AY,AZ).

Input: NCODE: Code specifying the curve fitted between material path points.

(X1,Y1,Z1): (X2,Y2,Z2) (x,y,z) coordinates of the end points of a material path line.

N2: Number of points along a material path curve.

C1,C2: Coefficients of the polynomial curve.

Output: (AX,AY,AZ): (x,y,z) components of the tangent vectors. AX,AY and AZ are single-dimensioned arrays of size N2.

Basis: See Appendix D.

Subroutine TANV

Purpose: Given three points on the boundary of a cross-sectional plane, a vector tangent to the middle point is constructed.

Calling Sequence: Call TANV (X1,Y1,X2,Y2,X3,Y3,BX,BY).

Input: (X1,Y1): (X2,Y2) (X3,Y3) (x,y) coordinates of the three points on the cross-sectional boundary.

(BX,BY): (x,y) components of the tangent vector.

Basis: See Appendix D.

Subroutine NORV

Purpose: This subroutine calculates a vector normal to two vectors using vector cross product.

Calling Sequence: Call NORV (AX,AY,AZ,BX,BY,BZ,RX,RY,RZ)

Input: (AX,AY,AZ): (BX,BY,BZ) (x,y,z) components of the two vectors.

Output: (RX,RY,RZ): (x,y,z) components of the normal vector.

Basis: See Appendix D.

Subroutine IGSINT

Purpose: This routine initializes the IGS package system. It is hardware dependent.

Subroutine PLOT

Purpose: This is used to plot the cutter paths on CRT screen. It is also hardware dependent.

Subroutine VIEWCH

Purpose: This is used to change the angle of the isometric plot of the cutter path.

## Subroutine CHECKNC

**Purpose:** For given tool position, this routine checks if the tool will undercut the surrounding die surface. If undercutting is detected, the designer is warned and is given the option to change the size of the cutter.

**Calling Sequence:** Call CHECKNC (I,J,XCUT,YCUT,ZCUT,N1,N2,N,KERR, THETA).

**Input:** I,J: Specify the point on the die surface.

XCUT,YCUT,ZCUT: Coordinates of the position of the cutter.

N1,N2: Number of points along the cross-sectional boundary and material path curve respectively.

N: N is related to the number of surrounding points at which the undercutting is checked.

KERR: Number used to control the execution of the subroutine.

THETA: Angle of the isometric view of the cutter path. Other input is via the common locations.

**Output:** KERR: Number used to control the execution of program DIENC.

**Basis:** See Appendix D.

# APPENDIX F

## MANUFACTURE OF EXTRUSION DIES

## APPENDIX F

## MANUFACTURE OF EXTRUSION DIES

This appendix gives the detailed dimensions and the procedure used in manufacturing the dies for the extrusion trials. For extruding round and rectangular shapes, three different dies were made. Figures F-1 to F-3 show the shapes and dimensions of these dies.

### Streamlined Die - D3

This die was used to extrude a rectangular shape from a cylindrical billet. Computer-aided design and computer-aided manufacturing (CAD/CAM) techniques, developed in this project, were utilized to design and manufacture this die.

The first step in the design of this die was the selection of die height (or length). Since the optimum die configuration depends on the flow stress of the material being extruded, three different optimal die lengths were obtained from the computer program "SHAPE" corresponding to the three materials (Cu 110, Al 6063, Al 7075) extruded through this die. A length of 1.158 inches was selected as a compromise of the three optimal lengths.

Next, the die surface and the cutter path for NC (Numerical Control) machining of the EDM electrode were determined from SHAPE. In the input data, the dimensions of the billet and the rectangular shape were reduced by 0.003 inch/linear dimension to accomodate EDM allowance.

The data on coordinates of the cutter path were used by the post-processor to generate the NC tape, which is then used to machine the graphite EDM electrode seen in Figure 3-12a.

The die block was machined from hot-work die steel, heat treated to proper hardness and then ground on outside diameter and faces. The graphite electrode was then sunk in the die block to machine the die surface by EDM process. Polishing of the die surface was done by hand. Figure 3-11 shows the die made by this process.

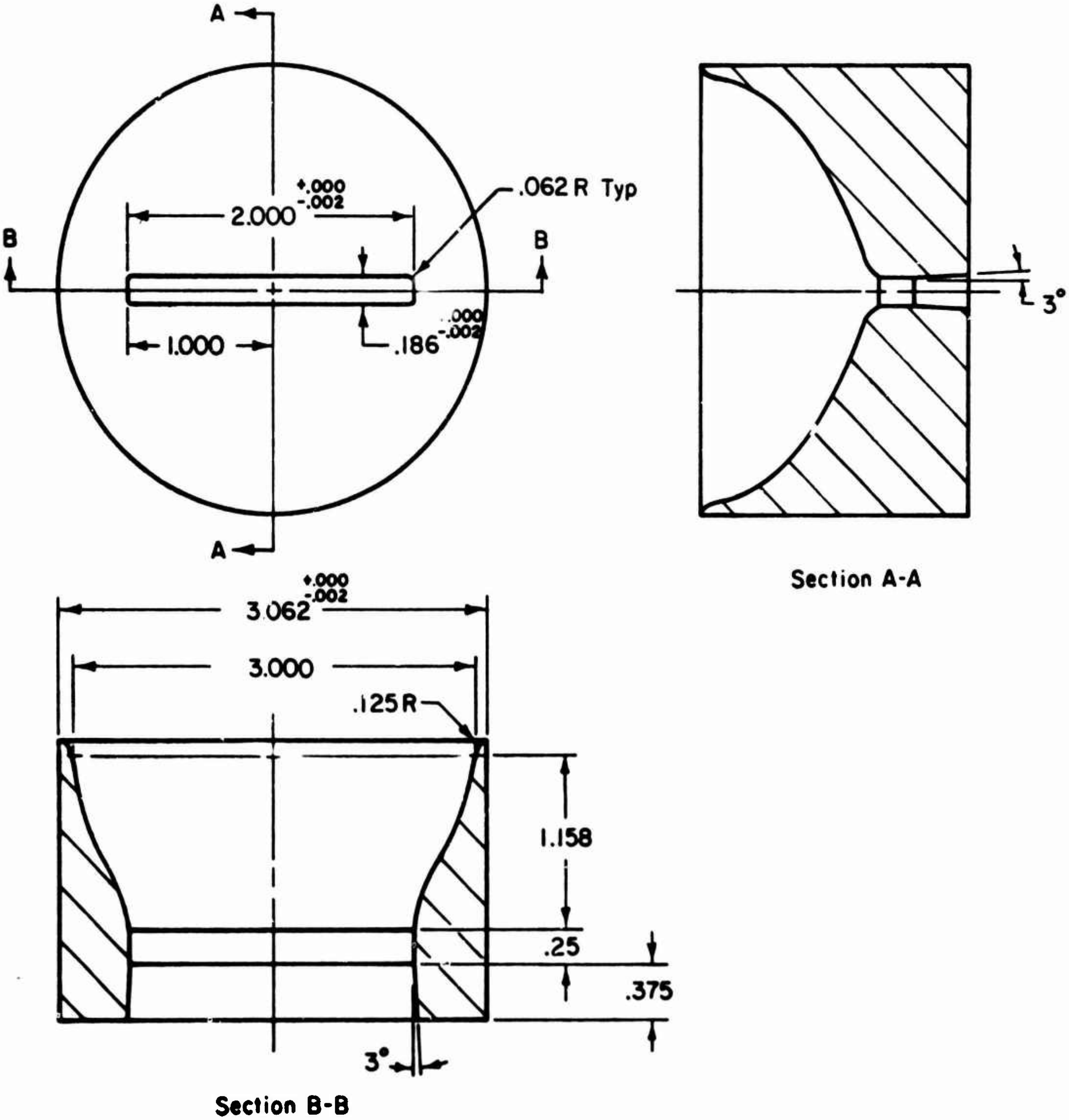



FIGURE F-1. STREAMLINED DIE - D3 FOR EXTRUDING A RECTANGULAR SHAPE FROM ROUND BILLET

(Heat treated to $R_c$ 43-46, Material H11, H12, or H13)

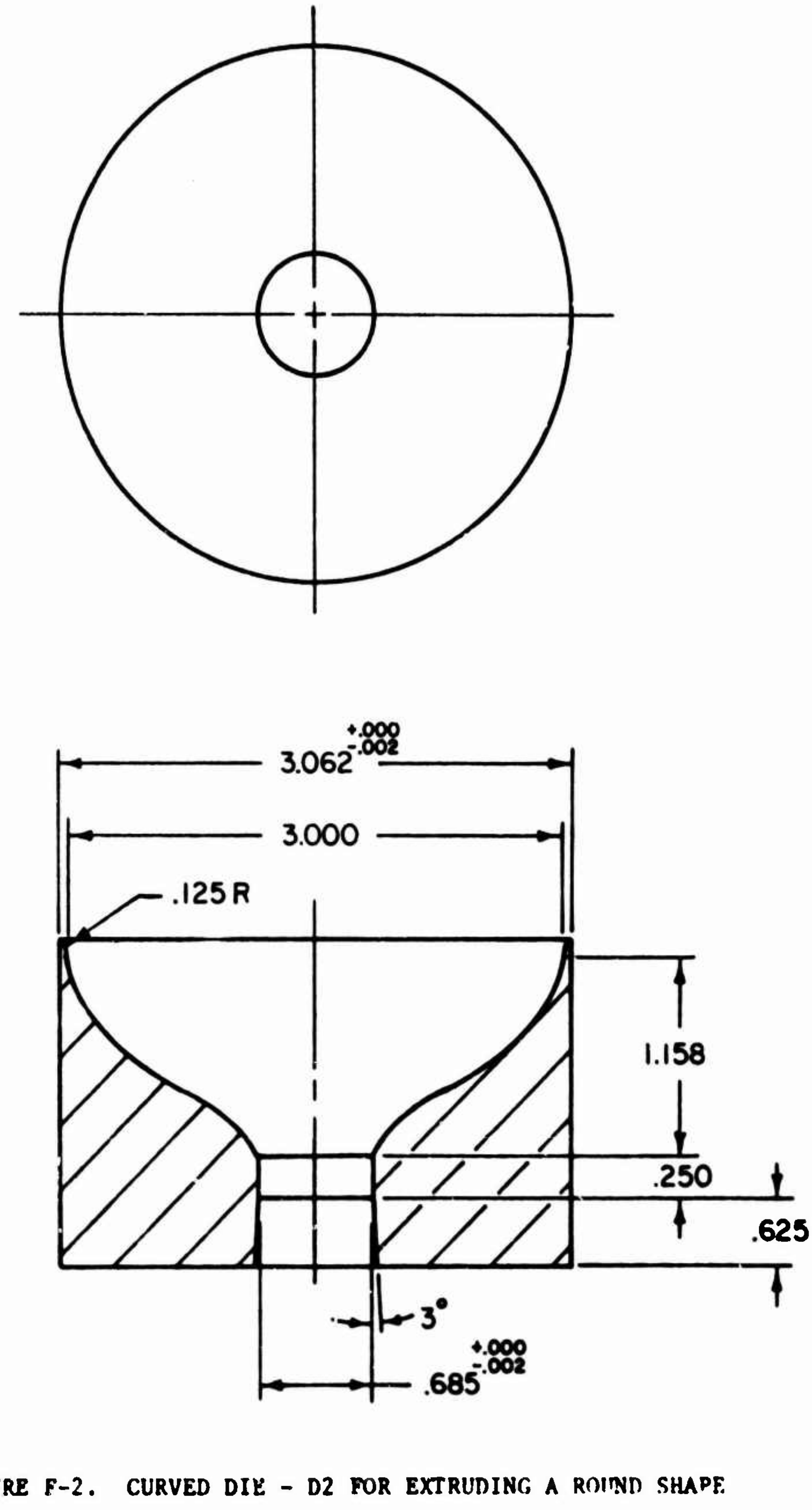



FIGURE F-2. CURVED DIE - D2 FOR EXTRUDING A ROUND SHAPE

(Heat treated to $R_c$ 43-46, Material H11, H12, or H13)

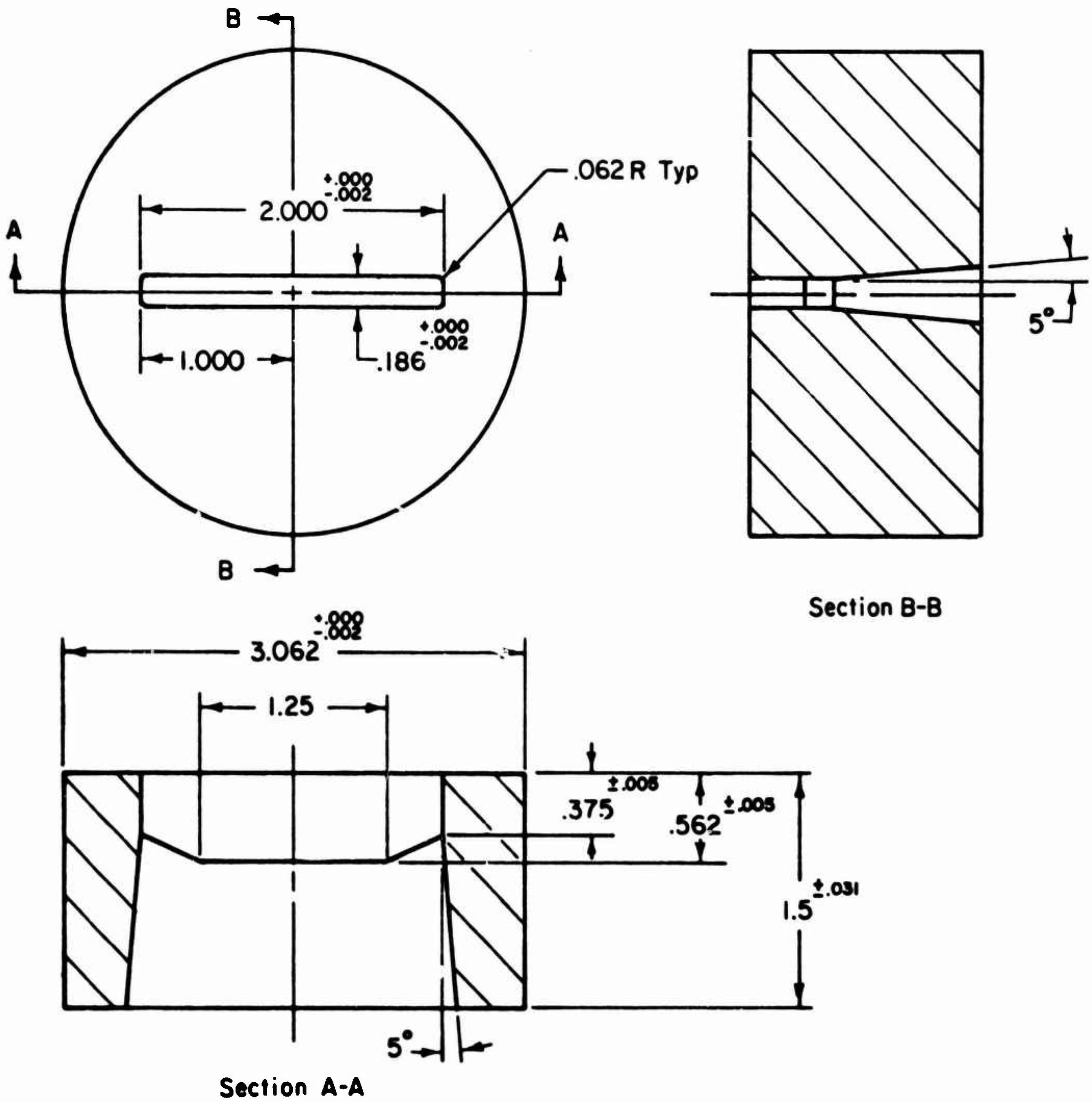



FIGURE F-3. FLAT-FACE DIE - D1 FOR EXTRUDING A RECTANGULAR SHAPE FROM A ROUND BILLET

(Heat treated to $R_c$ 43-46, Material H11, H12, or H13)

Curved Die - D2

To make a fair comparison of extrusion loads for extruding round and rectangular shapes, the length of the die, D2, for the round shape was kept the same as that of streamlined die, D3, for the rectangular shape. The die surface was chosen to be of polynomial form with zero entrance and exit angles (see Appendix D, page D-9). The coefficients $C_1$ and $C_2$ of the polynomial curve. were taken to be zero, since the study on extrusion of an elliptic shape had shown that the extrusion load is only slightly affected by these coefficients.

To machine the die surface by copy turning, a special template was NC machined. The die was machined by copy turning to final dimensions. The die was then heat treated and ground on outside diameter, inside diameter and flat faces. Finally, the die surface was polished by hand. Figure 3-12 shows the finished die.

Flat-Faced Die - D1

As seen in Figure F-3, the width of the die land of the flat-faced die is designed to obtain a uniform metal flow at the exit. The relative dimensions of the die land were calculated using the relation:

$$\frac{\ell_1}{\ell_2} = \frac{P_1}{A_1} \frac{A_2}{P_2} \quad , \tag{F-1}$$

where $\ell_i$, $P_i$, $A_i$ = effective land width, perimeter and cross sectional area, respectively, of the portion "i" of the die cavity.

The die block was turned, heat treated, and then ground on OD and faces. The die cavity was sunk by special EDM electrodes from front and back to give the desired die cavity and die-land configuration. The die land was polished by hand.

Army Materials & Mechanics Research Center
Watertown, Massachusetts 02172

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM, AND STEEL STRUCTURAL SHAPES-PHASE I

V. Nagpal and T. Altan
Battelle's Columbus Laboratories
Columbus, Ohio 43201

Technical Report - March 1976

96 pages, illustrations, tables, Contract DAAG46-75-C-0054
D/A Project 1497.94.5 S8154 (XR5)

Final Report, February 10, 1975, to February 10, 1976

Key Words

Computer-Aided Design
CAD/CAM
Extrusion
Die Designs
Aluminum Alloys
Titanium Alloys
Steel

The objective of this manufacturing technology program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys. The Phase-I work reported here was devoted to develop the CAD/CAM method for extruding a modular shape of rectangular cross section. The work covered (a) the review of die design for extrusion of structural shapes, (b) CAD/CAM of a streamlined die for a modular shape, and (c) CAD/CAM of streamlined dies for lubricated extrusion of simple structural shapes.

Army Materials & Mechanics Research Center
Watertown, Massachusetts 02172

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM, AND STEEL STRUCTURAL SHAPES-PHASE I

V. Nagpal and T. Altan
Battelle's Columbus Laboratories
Columbus, Ohio 43201

Technical Report - March 1976

96 pages, illustrations, tables, Contract DAAG46-75-C-0054
D/A Project 1497.94.5 S8154 (XR5)

Final Report, February 10, 1975, to February 10, 1976

Key Words

Computer-Aided Design
CAD/CAM
Extrusion
Die Designs
Aluminum Alloys
Titanium Alloys
Steel

The objective of this manufacturing technology program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys. The Phase-I work reported here was devoted to develop the CAD/CAM method for extruding a modular shape of rectangular cross section. The work covered (a) the review of die design for extrusion of structural shapes, (b) CAD/CAM of a streamlined die for a modular shape, and (c) CAD/CAM of streamlined dies for lubricated extrusion of simple structural shapes.

Army Materials & Mechanics Research Center
Watertown, Massachusetts 02172

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM, AND STEEL STRUCTURAL SHAPES-PHASE I

V. Nagpal and T. Altan
Battelle's Columbus Laboratories
Columbus, Ohio 43201

Technical Report - March 1976

96 pages, illustrations, tables, Contract DAAG46-75-C-0054
D/A Project 1497.94.5 S8154 (XR5)

Final Report, February 10, 1975, to February 10, 1976

Key Words

Computer-Aided Design
CAD/CAM
Extrusion
Die Designs
Aluminum Alloys
Titanium Alloys
Steel

The objective of this manufacturing technology program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys. The Phase-I work reported here was devoted to develop the CAD/CAM method for extruding a modular shape of rectangular cross section. The work covered (a) the review of die design for extrusion of structural shapes, (b) CAD/CAM of a streamlined die for a modular shape, and (c) CAD/CAM of streamlined dies for lubricated extrusion of simple structural shapes.

Army Materials & Mechanics Research Center
Watertown, Massachusetts 02172

AD ______________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM, AND STEEL STRUCTURAL SHAPES-PHASE I

V. Nagpal and T. Altan
Battelle's Columbus Laboratories
Columbus, Ohio 43201

Technical Report - March 1976

96 pages, illustrations, tables, Contract DAAG46-75-C-0054
D/A Project 1497.94.5 S8154 (XR5)

Final Report, February 10, 1975, to February 10, 1976

Key Words

Computer-Aided Design
CAD/CAM
Extrusion
Die Designs
Aluminum Alloys
Titanium Alloys
Steel

The objective of this manufacturing technology program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys. The Phase-I work reported here was devoted to develop the CAD/CAM method for extruding a modular shape of rectangular cross section. The work covered (a) the review of die design for extrusion of structural shapes, (b) CAD/CAM of a streamlined die for a modular shape, and (c) CAD/CAM of streamlined dies for lubricated extrusion of simple structural shapes.

# US ARMY AVIATION SYSTEMS COMMAND
## DISTRIBUTION LIST

| No. of Copies | To |
|---|---|
| | Commander, US Army Aviation Systems Command, P.O. Box 209, St. Louis, Missouri 63166 |
| 10 | ATTN: AMSAV-EXT |
| 1 | AMSAV-FE (Cliff Sims, Maint Engr) |
| 1 | AMSAV-EQ (C. Crawford, Sys Dev & Qual) |
| 1 | AMSAV-FES (H. Bull, Corpus Christi) |
| 2 | AMSAV-ZDR (Ref Library) |
| | Project Manager, Advanced Attack Helicopter, P.O. Box 209, St. Louis, Missouri 63166 |
| 1 | ATTN: AMCPM-AAH, TM |
| | Project Manager, Utility Tactical Transport Aircraft System, P.O. Box 209, St. Louis, Missouri 63166 |
| 1 | ATTN: AMCPM-UA-T |
| | Project Manager, CH-47 Modernization, P.O. Box 209, St. Louis, Missouri 63166 |
| 1 | ATTN: AMCPM-CH47M |
| | Project Manager, Advanced Scout Helicopter, P.O. Box 209, St. Louis, Missouri 63166 |
| 1 | ATTN: AMSAV-SIA |
| | Project Manager, Aircraft Survivability Equipment, P.O. Box 209, St. Louis, Missouri 63166 |
| 1 | ATTN: AMCPM-ASE-TM |
| | Project Manager, Cobra, P.O. Box 209, St. Louis, Missouri 63166 |
| 1 | ATTN: AMCPM-CO-T |
| | Project Manager, Iranian Aircraft Program, P.O. Box 209, St. Louis, Missouri 63166 |
| 1 | ATTN: AMCPM-IAP-T |
| | Commander, US Army Materiel Command, 5001 Eisenhower Avenue, Alexandria, Virginia 22333 |
| 4 | ATTN: AMCRD-TE |
| | Director, Eustis Directorate, US Army Air Mobility R&D Lab, Ft. Eustis, Virginia 23604 |
| 1 | ATTN: SAVDL-EU-TAS |
| | Director, Ames Directorate, US Army Air Mobility R&D Lab, Ames Research Center, Moffett Field, California 94035 |
| 1 | ATTN: SAVDL-AM |

| No. of Copies | To |
|---|---|
| | Director, Langley Directorate, US Army Air Mobility R&D Lab, Mail Stop 266, Hampton, Virginia 23365 |
| 1 | ATTN: SAVDL-LA |
| | Director, Lewis Directorate, US Army Air Mobility R&D Lab, 21000 Brook Park Rd, Cleveland, Ohio 44135 |
| 1 | ATTN: SAVDL-LE |
| | Director, Production Equipment Agency, Rock Island Arsenal, Rock Island, Illinois 61201 |
| 1 | ATTN: AMXPE-MT |
| | Air Force Materials Laboratory, Manufacturing Technology Division Wright-Patterson Air Force Base, Ohio 45433 |
| 1 | ATTN: AFML/LTM |
| 1 | AFML/LTN |
| 1 | AFML/LTE |
| | Commander, US Army Electronics Command, Ft. Monmouth, New Jersey 07703 |
| 1 | ATTN: AMSEL-RD-P |
| | Commander, US Army Missile Command, Redstone Arsenal, Alabama 35809 |
| 1 | ATTN: AMSMI-IIE |
| | Commander, US Army Troop Support Command, 4300 Goodfellow Blvd., St. Louis, Missouri 63120 |
| 1 | ATTN: AMSTS-PLC |
| | Commander, US Army Armament Command, Rock Island, Illinois 61201 |
| 1 | ATTN: AMSAR-PPR-1W |
| | Commander, US Army Tank-Automotive Command, Warren, Michigan 48090 |
| 1 | ATTN: AMSTA-RCM.1 |
| 12 | Commander, Defense Documentation Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, Virginia 22314 |
| | Hughes Helicopter, Division of Summa Corporation, M/S T-419, Centinella Avenue and Teale Street, Culver City, California 90230 |
| 2 | ATTN: Mr. R. E. Moore, Bldg. 314 |
| | Sikorsky Aircraft Division, United Aircraft Corporation, Stratford, Connecticut 06497 |
| 2 | ATTN: Mr. Stan Silverstein, Section Supv., Manufacturing Technology |
| | Bell Helicopter Company, P.O. Box 482, Ft. Worth, Texas 76101 |
| 2 | ATTN: Mr. P. Baumgartner, Chief, Manufacturing Technology |

| No. of Copies | To |
|---|---|
| | Kaman Aerospace Corporation, Bloomfield, Connecticut 06002 |
| 2 | ATTN: Mr. A. S. Falcone, Chief of Materials Engineering |
| | Boeing Vertol Company, Box 16858, Philadelphia, Pennsylvania 19142 |
| 2 | ATTN: R. Pinckney, Manufacturing Technology |
| | Detroit Diesel Allison Division, General Motors Corporation, P.O. Box 894, Indianapolis, Indiana 46206 |
| 2 | ATTN: James E. Knott, General Manager |
| | General Electric Company, 10449 St. Charles Rock Road, St. Ann, Missouri 63074 |
| 2 | ATTN: Mr. H. Franzen |
| | AVCO-Lycoming Corporation, 550 South Main Street, Stratford, Connecticut 06497 |
| 2 | ATTN: Mr. V. Strautman, Manager, Process Technology Laboratory |
| | United Technologies Corporation, Pratt & Whitney Aircraft Division, Manufacturing Research and Development, East Hartford, Connecticut 06108 |
| 2 | ATTN: Mr. Ray Traynor |
| | Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172 |
| 2 | ATTN: DRXMR-PL |
| 1 | DRXMR-PR |
| 1 | DRXMR-CT |
| 1 | DRXMR-XC |
| 1 | DRXMR-AP |
| 1 | DRXMR-M |
| 36 | DRXMR-E |

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

## REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AVSCOM 76-12

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

9

4. TITLE (and Subtitle): Computer-Aided Design and Manufacturing for Extrusion of Aluminum, Titanium, and Steel Structural Parts (Phase I).

6

5. TYPE OF REPORT & PERIOD COVERED: Final Report. 10 Feb 75- ~~2/10/75 - 2/10/76~~ 10 Feb 76

6. PERFORMING ORG. REPORT NUMBER: AMMRC ~~CTR~~ 76-6

7. AUTHOR(s): Vijay/Nagpal, Taylan/Altan

10

8. CONTRACT OR GRANT NUMBER(s): 15 DAAG46-75-C-0054 NEW

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: D/A Project: AMCMS Code: 1497.94.5.S8154(XR-5) Agency Accession:

11. CONTROLLING OFFICE NAME AND ADDRESS: Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172

11

12. REPORT DATE: March 1976

13. NUMBER OF PAGES: 187

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Army Materials & Mechanics Research Center, Watertown, Massachusetts 02172

12 213p.

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 AMMRC, USAAVSCOM

19 CTR-76-6, 76-12

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computer-Aided Design
CAD/CAM
Extrusion
Die Design
Aluminum Alloys
Titanium Alloys
Steel

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)


The overall objective of this program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys.

This report covers the Phase-I work conducted in this program. This work was completed by performing the following major tasks: (a) review the present state of the art in extrusion die design and characterize the most


DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 407080

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

LB

commonly used extruded shapes, (b) divide these shapes into geometric modules and develop the CAD/CAM techniques for extruding a modular shape, (c) expand the results of the analysis, developed for a modular shape, to more practical simple shapes, such as L's, T's, and rectangles, and (d) perform extrusion trials with a rectangular shape to demonstrate the validity of CAD/CAM techniques.

In order to enhance readability, the results of Phase-I work are presented in the form of three chapters as follows: (1) Die Design for Extrusion of Structural Shapes, (2) CAD/CAM of a Streamlined Die for a Modular Shape, (3) CAD/CAM of Streamlined Dies for Lubricated Extrusion of Simple Structural Shapes.